Why economic analysis supports strong action on climate change: a response to the Stern Review's critics[1]

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Abstract

Economic research that opposes the strategy of strong and urgent reductions in greenhouse gas emissions often makes the observation, misleadingly, that while scientists, environmentalists, politicians and others would favour strong action, economists would not. Drawing on the Stern Review on the Economics of Climate Change, this paper argues that strong and urgent action is in fact good economics. Much of the previous economic literature on climate change has failed to grasp the necessary scale and timing of action because it has failed to simultaneously assign the necessary importance to issues of risk and ethics. The case for strong and urgent action set out in the Review is based, first, on the severe risks that the science now identifies and, second, on the ethics of the responsibility of current generations for future generations. It is these two issues-- risk and ethics --that are crucial.

Keywords

Climate change; discounting; ethics; risk; uncertainty

JEL classification

A11; H43; Q54

1. Introduction and Summary

Economic research that opposes the strategy of strong and urgent reductions in greenhouse gas (GHG) emissions, such as the contributions in this issue by Robert Mendelsohn [citation-publisher will insert] and by John Weyant [citation-publisher will insert], usually makes a distinction between scientists, environmentalists, politicians and others who favour strong action, and economists, who apparently do not. Drawing on the Stern Review on the Economics of Climate Change (Stern, 2007), this paper shows that strong and urgent action is in fact good economics. Much of the previous economic literature on climate change has failed to grasp the necessary scale and timing of action (notable exceptions include Cline, 1992, and Azar and Sterner, 1996), because it has failed to *simultaneously* assign the necessary importance to issues of *risk* and *ethics*. The case for strong and urgent action set out in the Review is based, first, on the severe risks that the science now identifies (together with the additional uncertainties[2] that it raises but that are difficult to quantify) and, second, on the ethics of the responsibility of current generations for future generations. It is these two issues--risk and ethics--that are crucial.

We begin in section two with a clear explanation of the three modes of assessment used by the Review to evaluate the necessary scale and timing of action to reduce GHG emissions. Central to many critiques of the Review[3] is a fundamental misunderstanding of the role of formal, highly aggregated economic modelling in evaluating a policy issue that is characterised by a very long timeframe, profound ethical considerations, great uncertainty, market imperfections, limited policy instruments and a requirement for international collaboration. Formal models can and should play an important role in the systematic and transparent exploration of assumptions and value judgements, and how they affect the scale and structure of policy. But to base real-world policy on the minimisation of the present value of the costs of climate change and the costs of abating GHG emissions in a formal model – what Mendelsohn [citation] *equates* with ‘economic analysis’ – is both misleading and dangerous. Economists can and do make use of a much broader range of analysis in formulating policy recommendations. Sound economic policy-making requires assembling all of the available evidence in a structured way. Formal modelling is helpful in this respect but necessarily omits a great deal of what is important and further risks building conclusions on strong assumptions about the modelling structures, which are often chosen for analytical convenience more than anything else (Atkinson and Stiglitz, 1980; Deaton and Stern, 1986).

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[2] Where we distinguish between risk and uncertainty, we adopt the “Knightian” approach to the latter concept: i.e. it corresponds to circumstances where we are not in a position to attach probabilities to uncertain events (Knight, 1921).

[3] For example Mendelsohn [citation] and Weyant [citation], as well as Dasgupta (2006), Neumayer (2007), Nordhaus (2006), Tol and Yohe (2006 and 2007), and Weitzman (2007)

In sections three and four we review the nature of the risks and uncertainties surrounding the cost of business-as-usual (BAU) climate change, compared with the cost of emission reductions. Robert Mendelsohn [citation] accuses us of overestimating the cost of climate change on the one hand, and underestimating the cost of emission reductions on the other. Similarly (if rather more circumspectly), John Weyant [citation] emphasises that the cost of emission reductions is uncertain. While we do not disagree with Weyant's observation, the key message of this section is that the risks and uncertainties surrounding the impacts and costs of BAU climate change are much greater than those surrounding the costs of emission reductions. That is to say, the highest damages (plus adaptation costs) that we could expect as a result of climate change are much higher than the highest possible costs of mitigation.

This is broadly the structure of risk in climate-change policy. Some analysts seem willing to run such risks (e.g. Mendelsohn, [citation], and Nordhaus, 2006), because they fall largely on future generations, and because discounting the benefits of reducing these risks at a relatively high rate renders them insignificant. Any discussion of discounting for the economics of public policy derives from a discussion of intertemporal values. Thus in section four we contend that ethics must be at the heart of the economic analysis and cannot be put to one side. The consequences of different values should be explored and clarified. We believe that most people would find the conclusion above unethical. Moreover, we must recognise that the risks posed by climate change raise a set of ethical issues that go far beyond those related to discounting.

Uncertainty, and the prospect of resolving some of it in the future, is often used as a justification for delaying action (i.e., waiting to see whether the consequences of climate change are indeed as severe as now seems possible, and whether the cost of emission reductions is indeed as low as now seems likely). We conclude our paper in section five by explaining why a sensible approach to risk implies that this is precisely the wrong conclusion. Even though we will have the opportunity to revise global efforts to abate GHG emissions in the future, the balance of the evidence points to setting as a matter of priority a clear and tight target for a stable concentration of GHGs in the atmosphere.

2. Economic analysis of climate-change policy

Economists view climate change as an externality and, as such, can call upon a number of familiar analytical techniques. In the case of a 'textbook' externality (i.e., in an economy without further distortions from taxes, externalities, market power, imperfect information and so on and assuming a particular model of utility and social welfare), the recommendation will be to carefully calculate, in terms of its present monetary value, the social cost of the externality and to correct it, up to the point where the marginal social benefit of doing so is just equal to the marginal social cost.[4] Even for a relatively simple externality, however, there is a big gap between textbook and reality; for example, limits to information, multiple ethical objectives, unrepresented consumers and so on demand a broader range of evidence. This gap between theory and reality is magnified many times over in the analysis of climate-change policy, because climate change is an externality with a unique combination of features:

- It is global in its causes and consequences. The contribution of GHGs to warming is broadly the same wherever in the world they are emitted, but the impacts of climate change will be highly uneven;
- The impacts of climate change are long-term and persistent. Once emitted, GHGs can reside in the atmosphere for many decades (carbon dioxide can reside there for over a century), and there is a lag in the response of the climate system to emissions. This means the marginal cost of GHGs emitted today lasts for hundreds of years. Thus climate change is a flow-stock problem and is slow and difficult to bring under control;
- The risks and uncertainties surrounding these impacts are pervasive;
- There is a risk of major, irreversible change with economic effects that are non-marginal to the future path of global growth and development.

Any analysis that avoids taking on these elements explicitly is using a conceptual and analytical framework which fails to come to terms with the essentials of the problem. Simply put, the challenge is to use the right kind of public economics, rather than to rely solely on the undergraduate world of first-best simplifications for ‘perfect’ economies.

Consequently the Review’s assessment was built on three lines of investigation. The simplest and most important comparison to be made is between our disaggregated analysis of the physical impacts of climate change on multiple dimensions (e.g. water and food availability, health and infrastructure: Chapters 1, 3, 4 and 5), and ‘bottom-up’ estimates of the costs of specific mitigation strategies, based on different portfolios of technologies (Chapter 9 and Anderson, 2006). The key question that policy-makers should ask is whether paying an insurance premium equal to the cost of mitigation for a given path to stabilise atmospheric GHG concentrations is worthwhile to reduce the risks and uncertainties described under BAU. This question is central, because it presents the basic policy problem as simply and transparently as possible, thereby avoiding the process of aggregating risks and uncertainties across

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[4] With appropriate intertemporal assessment and still further strain on assumptions, over time this can be seen as minimising the present-value sum of external costs and abatement costs (cf. Mendelsohn [citation], in this issue).

all dimensions (e.g. nations, time, goods etc.), a process for which information and data are extremely thin and which ignores or suppresses so much of what is important.

Nevertheless, formal economic models are useful for exploring particular, stylised aspects of the problem, such as the role of attitudes toward intergenerational equity and risk in estimating the cost of climate change, and the role of behavioural changes in the economy as a whole in determining the cost of mitigation. Thus the second line of investigation in the Review introduced the results of integrated assessment models of the cost of future climate change (impacts and adaptation: Chapter 6) and macroeconomic models of the cost of mitigation (Chapter 10). We issued, rightly in our view, strong warnings against a literal interpretation of these models and their results, warnings that all too many analysts appear to have ignored.

Chapter 13 of the Review brings together all this information in a third line of investigation. Through an informal price-based approach, we compared the expected costs of shifting from one path of emission reductions to another (e.g. moving from a stabilisation target of 650 to 550 parts per million of carbon dioxide equivalent [ppm CO_2e]) with the expected benefits of doing so. We expressed expected benefits not only in terms of formally estimated monetary benefits, but also in terms of reductions in basic risks to human wellbeing and to the environment (e.g. reduced risks of food and water shortages).[5] We summarised the consequences of different stabilisation targets in Figure 13.4 of the Review, which we reproduce here in Appendix 1. From this summary, the reader can transparently judge the benefits of incrementally tightening the target from 750 ppm CO_2e to 400 ppm CO_2e. This can be compared with a range of estimates of the costs of doing so, which is also summarised in Chapter 13. Thus Mendelsohn [citation] is mistaken in suggesting that we only compared the costs of BAU climate change with “one, near-term aggressive abatement policy”.[6]

3. The cost of mitigation and its uncertainties

The basic premise of this section and the next is that while we are uncertain about the cost of mitigation, we are much more uncertain about the cost of BAU climate change. We begin with the cost of mitigation.

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[5] The three approaches are, of course, logically related in a formal sense, but they represent different perspectives on the problem.

[6] Some other concerns have been raised, including by Mendelsohn in this issue, about the consistency between our analyses of the costs and benefits of mitigation, in terms of time periods of analysis, baseline scenarios of socio-economic development and emissions growth, discounting schedules and so on. We find no such inconsistencies and diligent readers are referred to the Appendix to Dietz *et al.* (2007a) for a detailed rebuttal of each charge.

The main finding from the Review's assessment of the cost of mitigation[7] is that the cost through time of keeping GHG emissions to a plausible pathway to stabilisation of atmospheric concentrations at 550 ppm CO_2e – which would be sufficient to significantly reduce many of the risks of BAU climate change (see Appendix 1) – is 1% of global GDP through the end of this century. As carefully explained in Chapter 13, stabilisation is likely to be cheaper at higher concentrations than at lower concentrations. We are uncertain about how much mitigation techniques and technologies will cost in the future, when and where they will be used, and in what combination. Thus we placed around our central estimate a range of +/-3 percentage points of GDP. Since publication of the Review, studies by Enkvist *et al.* (2007), the International Energy Agency (IEA, 2006) and IPCC (2007a) have reported similar central estimates and ranges. These range, though large, are still much narrower than the range one has to consider for the cost of climate change.

Stabilising atmospheric GHG concentrations at 550 ppm CO_2e or lower will certainly require deep cuts in global emissions. The atmospheric stock of GHGs is currently around 430 ppm CO_2e and the rate of addition to that stock is around 2.5 ppm per annum and rising quickly. If stabilisation at 550 ppm CO_2e is to be achieved, total global emissions will have to peak in the next 10-20 years. By 2050, total global emissions will have to be around 25% less than current levels (given growth of the global economy in the intervening years, they will have to be around 75% less per unit of GDP).[8] To stabilise at 450 ppm CO_2e (without overshooting and then coming back down to that level, a risky pathway), total global emissions will need to peak even sooner (in the next 10 years), falling to 70% less than current levels by 2050.

Thus what the Review recommends constitutes nothing less than a strong and sustained reduction in the volume of GHGs emitted by global economic activity. Yet an examination of the ways in which this can be achieved shows that it is both technically and economically feasible and at a cost, which, while significant, is small in comparison with the range of benefits of doing so, at least up to the 450-550 ppm CO_2e range (i.e., this conclusion is unlikely to apply to even lower stabilisation targets, essentially because we have already passed them). This reduction is technically feasible, because there is already a set of techniques available today for achieving stabilisation (e.g. Pacala and Socolow, 2004).[9] Moreover, further research and development should broaden and deepen that set.

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[7] This appears principally in Chapters 9 and 10, though all of Part III is relevant to the story.

[8] In the longer run, they will have to fall much further, to bring them in line with the Earth's natural capacity to remove GHGs from the atmosphere.

[9] One example is an increase in the fuel economy of all cars projected for 2050, from 30 miles per gallon (mpg) to 60 mpg.

It is economically feasible because the evidence tells us that within the feasible set of abatement opportunities there are many to be exploited at a very low (perhaps in some cases even a negative) cost. For the other opportunities (principally new, low-emission technologies), the increase in cost seems manageable. Roughly 40% of global emissions derive from non-fossil fuel sources and here reductions could be won at a low cost. One example is avoiding deforestation, which could cost less than \$5 per tonne of carbon dioxide (tCO_2) and perhaps as little as \$1/tCO_2, roughly equivalent to just 40 cents per barrel of oil (Grieg-Gran, 2006).[10] Another source of emission reductions is improvements in energy efficiency. As the International Energy Agency's studies (e.g. IEA, 2006) have highlighted, there is considerable technical potential for energy efficiency to deliver emission reductions over the coming years. Since such efficiency improvements lead to reduced energy inputs for a given level of output, many of them will provide an economic benefit that is unrelated to the benefit of mitigating climate change: that is, they may come at a negative cost.

Therefore, the positive cost of mitigation to the global economy will mainly come from the need to deploy some mix of low-emission technologies to substitute away from fossil fuels. These technologies are currently more expensive than their fossil fuel-based counterparts. Even here, however, two factors are likely to limit the risk of high costs. First, the costs at present of such technologies are higher than incumbent high-emission technologies, but not by the orders of magnitude that would truly send the costs of stabilisation sky-rocketing (see our simple calculations below). Second, historical experience has repeatedly shown that the costs of technologies fall over time, through learning and economies of scale. So, low-emission technologies are likely to be even cheaper in the future, perhaps, in a small minority of instances, becoming cheaper than the 'marker' technology (i.e. the assumed, high-emission incumbent) even before emissions intensity is priced in.

The Review's quantitative assessment of these issues followed two approaches. The first surveyed the latest literature covering macroeconomic models of mitigation, a 'top-down' approach (Chapter 10). These models are capable of describing complex behavioural linkages and thus of simulating, for example, substitutions from high-emission to low-emission techniques in the face of changing relative prices. But with complexity comes opacity, and much turns on a series of assumptions about the evolution of behaviour, technologies and policy that can be difficult to decipher (making the meta-analyses of Fischer and Morgenstern, 2005, and Barker *et al.*, 2006, very valuable in isolating the approximate contribution of such assumptions). Because different assumptions are made in different studies, these models produce a range of estimates, summarised in the Review as a range of +/-3% of

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[10] Based on estimates of the opportunity cost of the land: in addition administration and enforcement costs will be incurred.

GDP. Weyant [citation] contends that the range is wider, up to 10% of GDP. However, we do not consider the high-end of this range to be credible, as these estimates apparently originate from modelling studies that treated technical change unrealistically (by ignoring either the possibility of a backstop technology[11] or possibilities to substitute away from high-emission technologies, so that the only option is to squeeze growth), or made pessimistic assumptions about the design of policy. In the Review, we were quite clear that, as Weyant is right to emphasise, flexible policy (in terms of where and when emission reductions are carried out, and what techniques are used and on what GHGs) will be important in keeping costs down. We set out to answer the question "what could mitigation costs be if the world acts quickly and flexibly?" rather than "what will costs likely be if the world drags its feet, waking up with a start much later on?”

Second, we also commissioned a simple and transparent cost-assessment exercise. In order to assess the likely costs of mitigation in a world where behavioural change is limited – a very conservative assumption in the sense that it underestimates flexibility and thus overestimates cost – a probabilistic projection of the evolution of low-carbon technologies and of fossil-fuel prices was used (Anderson, 2006), a ‘bottom-up’ approach. This study gave results in a range similar to the more complex behavioural modelling exercises. It showed that, under a *feasible* technology mix,[12] replacing carbon-intensive energy generation and transportation with low-carbon technologies to stabilise at 550 ppm CO_2e could be attained at a mean cost of approximately 1% of GDP by mid-century. The uncertainty around this mean amounted again to around +/-3 percentage points of GDP, reflecting in particular uncertainty about technological innovation and the evolution of fossil-fuel costs. Unlike the behavioural models, this approach offered a very simple and transparent way of making a first approximation of the likely cost of one route to stabilisation. For example, let’s take the assumptions made about learning curves (i.e., the rate at which technology costs fall with increasing scale of deployment). It is easy to see from Anderson (2006) that the assumptions about learning are conservative by historical standards.

To round up our discussion of mitigation costs, let us illustrate possible orders of magnitude using a simple but robust and transparent calculation, which is similar to Mendelsohn’s [citation] in this issue. Assume stabilisation at 550 ppm CO_2e requires global emission reductions of 40 billion tonnes of CO_2 per year by 2050. Taking the very upper end of our range of estimates of the average cost of abatement, \$100/tCO_2, stabilisation at 550 ppm CO_2e would cost \$4 trillion by 2050, or about 3.6% of global

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[11] This has a high cost, but infinite availability (formally, supply is totally elastic in price), and thus places an upper limit on the cost of mitigation in the sector in question.

[12] Not an *optimal* mix. Some critiques of this part of the Review, such as Mendelsohn’s in this issue, are wide of the mark, because they make two mistaken assumptions: first, that Anderson (2006) explored just one pathway (he explored thousands in a Monte Carlo analysis) and, second, that any one of these pathways is the one actually advocated by the Review.

GDP.[13] Now ask how high the average cost of abatement would have to be if Weyant [citation] were right in putting the upper end of the range of likely stabilisation costs at 10% of GDP. The answer using simple arithmetic is \$1000/tCO_2. The vast majority of low-emission technologies are already available at a much lower average cost than this (e.g., nuclear power, coal with carbon capture and storage [CCS], on- and offshore wind, solar, hydrogen production from coal with CCS, etc.) and should become still cheaper as they are deployed.

4. The cost of climate change and its uncertainties

A parallel assessment of the possible cost of climate change is not as reassuring. For the first 1-2°C of temperature rise, there will be some winners and some losers, while adaptation can play a significant role in controlling costs and capturing benefits. For example, high-latitude regions in the Northern Hemisphere are likely to experience longer growing seasons, providing new opportunities in agriculture. But even at low levels of warming, there will be significant impacts on vulnerable communities, for instance in indigenous Arctic communities and on low-lying Pacific islands.

But BAU climate change is most likely to commit us to more than 1-2°C warming as this century progresses, potentially much more. The consequences of this distinguish the structure of the risks posed by climate change from those posed by emission reductions. Recent probabilistic analyses of the sensitivity of global temperatures to increases in the atmospheric stock of GHGs indicate that BAU emissions could irreversibly commit us, this century, to 5ºC warming or more (IPCC, 2007b; Meinshausen, 2006; Murphy *et al*., 2004). A change of 5ºC is comparable to the difference between temperatures today and temperatures 10-12,000 years ago, when most of Northern Europe and North America were under hundreds of metres of ice. A further 5ºC would transform the Earth’s physical geography, putting economies and societies under severe pressure.

Large parts of Asia (home to well over one billion people) depend for their water supply on glacial meltwaters in the Himalaya region, but the giant ‘water tower’ that these glaciers comprise is being melted by warming. Regional events that could bring severe disruption with little advance warning include an intensified El Niño event, or widespread forest fires in Siberia or the Amazon. These could

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[13] In contrast, Mendelsohn’s calculations assume that: (1) the average cost of abatement estimated by the Review is \$400 per tonne of carbon and (2) stabilisation at 550 ppm CO_2e requires emission reductions of 40 billion tonnes of CO_2 per year by 2050; thus yielding (3) a total cost of \$16 trillion globally by 2050, or about 15% of GDP. But closer inspection reveals that he: (1) confuses the average cost per tonne of carbon with that per tonne of CO_2, which inflates any estimate by a factor of 3.7; (2) rounds up our highest estimate of the average cost rather than our central estimate (\$25/tCO_2); so that (3) his overall estimate using our numbers is off by \$15 trillion, or a factor of sixteen!

trigger an abrupt failure in monsoon rains and a significant fall in agricultural yields in key areas of Asia, Australia or Latin America, with implications for the global trade in commodities such as wheat and soya, as well as risks of human misery, social instability, and migration in densely populated regions of the world. Abrupt, large-scale and discontinuous changes that we must consider on a global scale include a weakening in the Atlantic Thermohaline Circulation (a part of the global 'conveyor belt' of water and air) and a collapse in the Greenland and/or West Antarctic Ice Sheets, eventually contributing meters to global sea levels. It is not clear how we could adapt to changes that are abrupt and global in scale. Even if we could, the costs are likely to be very large.

These risks were set out in detail in Chapters 1, 3, 4 and 5 of the Review. Integrated assessment models (IAMs) of the monetary cost of climate change were reviewed in Chapter 6. As Chapter 6 has been a particular focus for comment, we have already responded in the Postscript to the Review, as well as in Dietz *et al*. (2007a and 2007b), which includes a sensitivity analysis on a number of dimensions. Here we focus on two issues: first, the extent to which IAMs in general, and the Review's modelling in particular, incorporate the risks now being identified by the science; and, second, the role of discounting in calculating the social cost of these risks.

4.1. Risk in integrated assessment models

IAMs are unequal in their coverage of climate impacts and this is one of the principal reasons why they differ in their estimates. Some (e.g. Mendelsohn *et al*., 1998) confine their attention to a narrow set of 'market' sectors of the economy such as agriculture and forestry (where prices exist or can be imputed relatively straightforwardly). Direct, welfare-equivalent impacts on human health and ecosystems (so-called 'non-market' impacts, because no market prices exist) are omitted. Other IAMs, such as Tol's (2002) assessment, include a wide range of market and non-market impacts, but are restricted to gradual climate change. Such studies omit the possibility of abrupt, large-scale and discontinuous climatic changes, which recent climate science has identified (e.g. Schellnhuber *et al*., 2006).

In fact, *none* of the IAMs formally incorporates estimates of all of the impacts of climate change considered possible (see Downing *et al*., 2005; and Figure 6.3 in the Review). Some, such as Nordhaus and Boyer (2000), include very rough estimates of 'catastrophic risks', but still largely ignore such risks, because they take a 'best guess' of how much warming will come about. The problem is that catastrophic risks, at least as they are simulated in IAMs, are unlikely to be triggered by best-guess warming of around 2-3ºC this century. This is too sanguine a forecast, because climate science tells us to consider more rapid warming (see IPCC, 2007b, which projects up to 6.4ºC warming by 2100), and with it an increased risk of catastrophic climatic changes. Figure 1 makes this point: it shows the estimates of ‘climate sensitivity’ (i.e. the equilibrium change in global mean temperature due to a doubling in the atmospheric concentration of CO_2) made in three IAM studies, compared to two ranges from the science. Other studies have suggested that such catastrophic risks could be triggered by as little as 1ºC warming (see Schneider and Lane, 2006), although they consider only the physical process, rather than its social and economic impacts.

FIGURE 1 HERE

In the Review, we chose to carry out some of our own modelling, using the PAGE2002 IAM (Hope, 2006). In estimating climate risks as fully as the then state-of-the-art allowed, PAGE2002 offered a number of advantages. It includes estimates of market impacts, non-market impacts and the risk of large-scale discontinuities or ‘catastrophes’, making it as comprehensive as any of its peers. It is stochastic, using a Monte Carlo procedure to estimate probabilities. And it is calibrated to reflect the range of disagreement and uncertainty in the underlying scientific and economic literatures. Consequently, it yields estimates of the simple cost of climate change at a particular temperature or point in time that are close to the centre of the range of estimates produced by other models (see figure 2). Thus, contrary to the impression some critics have sought to create (e.g. Byatt *et al.*, 2006; Mendelsohn [citation]), the Review’s modelling is not inconsistent with the underlying literature in its quantification of the cost of climate change.[14] Where it does differ is, first, in formally modelling a wider range of possible temperature changes, and, second, in explicitly modelling aversion to the most severe climate risks.

FIGURE 2 HERE

To explain the latter point, we must recognise that all the links in the chain between GHG emissions and the economic impacts of climate change – each of which needs to be parameterised in an IAM – are of course subject to uncertainty. But most previous studies have failed to tackle this uncertainty. The simplest modelling strategy in the literature is deterministic, whereby a ‘best guess’ is made for each parameter. This is still very common. Most IAMs have also been set up at one time or another to run a

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[14] We suspect that Mendelsohn [citation] confuses the risk of extreme weather events such as hurricanes with the risk of catastrophic changes to the climate system (such as a collapse of the West Antarctic Ice Sheet) in his discussion of the cost of extreme weather events estimated by the Review. We have no idea, however, where in the Review he has found an estimate of the cost of extreme weather events that is 5% of global GDP by 2200. The additional, undiscounted cost of climate change in 2200 due to catastrophic climatic changes, under the Review’s baseline-climate scenario, is 3.2 percentage points. There is no corresponding estimate of the cost of extreme weather events and it is doubtful whether any of the studies on which PAGE2002 is calibrated (see Hope, 2006) provide such an estimate (Warren *et al.*, 2006).

Monte Carlo procedure, enabling climate impacts to be modelled probabilistically (e.g. Hope, 2006; Mastrandrea and Schneider, 2004; Plambeck *et al.*, 1997; Roughgarden and Schneider, 1999). Yet very few of these studies extend to an application of expected-utility analysis (exceptions are Tol, 1999 and 2003), where climate risks can be valued in relation to society's attitudes to taking such risks. This is the approach adopted by the Review. While expected-utility analysis is often used to investigate issues around learning and the resolution of uncertainty over time, it is surprising to us that it has not become the standard method of social-welfare valuation in this more simple exercise – estimating the cost of inaction under BAU. Of course, expected-utility analysis has its own problems in this context (e.g. Ellsberg, 1961; Kahneman and Tversky, 1979), but it is a standard 'workhorse' and the natural first step. In terms of welfare, it has an additive structure consistent with summation (or integration) over time and over people within a generation.

Putting all of this together, we must take account of the risk (however small) that climate-change costs could run into the equivalent of many tens of percent of global GDP by the middle of the next century, which is much higher than the highest estimates of mitigation costs. The Review did just this.[15] Still, the structure of risks included in the Review's formal modelling should be seen as *cautious* (figure 1 is an intuitive illustration of this), indeed perhaps too cautious (see Weitzman, 2007). The scenarios and parameter values chosen are within the ranges established in the existing literatures, but it is these existing literatures that constrain the ability of the modelling to keep pace with newly emerging risks.

4.2. Ethics and discounting

Most commentary on the Review has focused on the discount rates used to convert the cost of climate change in the future into a present value (e.g. Mendelsohn [citation] and Weyant [citation] in this issue, as well as Dasgupta, 2006, Nordhaus, 2006, and Weitzman, 2007). It is however a mistake to attempt to jump straight to discount rates in this type of intertemporal policy analysis where potential changes are very large. Discount rates are essentially marginal concepts corresponding to changes around a pre-specified path of economic growth. In the case of climate change, we must take account of the risk of economic effects that are non-marginal to the future path of global growth and development. That is, the risks of climate change mean that we cannot assume economic growth will continue on its present trajectory, if emissions continue to follow BAU. But as we explain below, the discount rate depends on what we assume about economic growth.

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[15] Interested readers could browse the confidence intervals around the cost of climate change over time, under different scenarios, reported in Figure 6.5, on page 178 of the Review.

Even within standard, medium-term cost-benefit analysis of marginal changes, it is a mistake to believe that we can know from market observation what those discount rates should be. Capital markets are full of distortions related to the role of information. Market rates of return on investments are not social rates of return – they generally take no account, for example, of environmental damages or other market distortions. There are all sorts of institutional factors affecting the choices governments make about required rates of return on investment, including gaming and 'optimism bias' from project sponsors. And there is very little market information for investment decisions over 50, 100 or 150 years. In sum, we do not see any markets that can reveal clear answers to the question "how do we, as a generation, value benefits to collective action to protect the climate for generations a hundred or more years from now?" (see Hepburn, 2006, and Dietz *et al.*, 2007b, for further discussion). These are not the allocations reflected in market decisions. There is indeed a discussion to be had about how much and how little current market information tells us. Yet, like Sterner and Persson [citation], we conclude that there is no shortcut to conducting a debate about discounting on the basis of first principles, which in turn puts ethics at centre-stage.

In formal economic modelling, the ethical discussion has focused primarily on attitudes toward inequality (via the elasticity of the social marginal utility of consumption, η) and the weight given to future generations (via the rate of pure time preference, δ). This is already a very narrow view of ethics, omitting for example notions of rights and responsibilities between and within generations. We should not overlook this basic point. Nevertheless, in these highly aggregated models, ethical considerations usually boil down to this simplistic structure. With the restrictive assumption of marginal changes in the absence of uncertainty and where g is the growth rate, the social discount rate r in these models is:

$$r = \eta g + \delta \tag{1}$$

Each element on the right-hand side of (1) has a different role. First, in this framework, η captures not only attitudes toward inter-generational distribution, but also toward risk and intra-generational distribution. Second, g is a feature of model structures and assumptions, not ethics. Higher g gives not only a higher social discount rate but also earlier emissions and hence earlier and higher damages from GHGs, as well as increasing adaptive capacity. Third, in the context of climate-change policy, δ is largely about ethical discrimination according to date of birth (apart from the probability of planetary demise: see Chapter 2 of the Review).

Let us consider each of these elements more carefully. First, we examine δ. We have not heard a serious ethical argument in favour of extreme values of δ of 2% or 3% per annum, which Nordhaus (2006) and

Weitzman (2007) appear to support. Different values of δ will be appropriate in different circumstances. The circumstances here are collective choices today to reduce global emissions of GHGs, providing potentially very large benefits across many generations. Seen in this light, it is very clear that δ should largely be understood in terms of ethical discrimination by birth date. It is not a question of an individual's impatience with respect to his/her own consumption in his/her own lifetime, nor should it include the larger set of risks to the survival of individual government projects, with a marginal effect relative to the overall growth path.[16] When interpreted as discrimination by birth date, extreme values of δ are difficult to justify. If $\delta = 2\%$, then someone born in 1972 would have twice the ethical weight of someone born in 2007. So if these two individuals were expected to have the same income, an extra unit of consumption to the one born in 2007 would be given only half the weight of an extra unit of consumption to the one born in 1972. Would many people regard this as ethically acceptable in terms of responsible social action? We think not. Further, a high δ can lead to a version of time inconsistency – each generation postpones action, because with a high δ each generation will also seek to minimise short-term mitigation costs, passing the burden on to the next generation.

Next, we examine growth, g. The growth assumptions in the formal modelling of Chapter 6 of the Review were fairly conservative: global growth starts at around 2.5% on aggregate (0.9% per capita, due to rapid population growth) and falls to around 1.8% (1.4% per capita) in the latter half of the 22nd century. However, it is certainly plausible that over a period of time global growth rates could be higher than this. This would have up to three effects on the assessment of future damages that would work in opposite directions: first, faster growth brings both earlier emissions and thus damages; second, higher future incomes bring greater discounting (before the effects of climate damages kick in hard). We have not formally modelled these effects but our judgement and preliminary assessments suggest that both effects are strong. In addition, faster growth could increase adaptive capacity, particularly in the developing world (see Dietz *et al.*, 2007a, for sensitivity analysis on adaptive capacity).

Finally, let us turn to η. Some have argued (e.g. Dasgupta, 2006) that $\eta = 1$ is too low. This is an ethical parameter and as such it is important to look at alternatives – as we did in the Postscript to the Review. What is an appropriate range? Many cost-benefit analyses essentially use $\eta = 0$: i.e. they weight an extra dollar to all individuals in the same way. This is problematic over an infinite horizon (see the Appendix to Chapter 2 of the Review). On the other hand, $\eta = 2$ implies a degree of aversion to inequality, and consequently a preference for redistribution, that seems inconsistent with many decisions taken today (also see Sterner and Persson [citation]). Let's conduct a simple 'leaky bucket' experiment. The question is, in redistributing income from a rich individual to a poor individual, how much would we be

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[16] Covered for example by the "Green Book" in the UK (HM Treasury, 2003).

prepared to lose along the way, for example through administrative costs? Those who argue $\eta = 2$ are by implication saying that taking one dollar from an individual A, who has five times the income of individual B, is a social improvement, provided no more than 96% gets lost in transfer (in other words, an extra dollar to individual B is worth 5 squared or 25 times that to individual A).

In considering a range of values of η and δ we have to go back to first principles. For η, we would suggest that the above discussion points to a reasonable range of between 1 and 2 for sensitivity analysis. However, we would suggest that the range of 1 to 1.5 is likely to be of greater interest to most ethical observers. We do recognise that the combination of $\eta = 1$ and $\delta = 0.1\%$ places a very high weight on the future (see the Appendix to Chapter 2 of the Review on convergence of utility integration). And we recognise that there is a plausible ethical case for a higher η. It is a mistake, however, to argue that $\eta = 1$ together with a low δ necessarily imply very high savings rates if incorporated into an optimum savings model (as Dasgupta, 2006, and Nordhaus, 2006, have done). The reason is that the optimum savings rates in such models also depend on assumptions about the structure of production, including technical progress. If, for example, technical progress contributes significantly to growth, then $\eta = 1$ together with a low δ are consistent with current rates of savings.

4.3. Risk and ethics together

The two fundamental issues guiding the appropriate strength and timing of climate-change policy are risk and ethics. Both are necessary foundations of the case for strong action, as we argued in the Review and demonstrated in the Postscript and in Dietz *et al*. (2007a and 2007b). In the Stern Review's base modelling case[17], we set $\delta = 0.1\%$ p.a., $\eta = 1$ and we took risk into account by calculating expected utility from a wide range of scenarios. The present value of the cost of climate change was equivalent to a 10.9% loss in global mean per capita consumption.[18] Previous studies, as well as some critiques of our formal modelling (e.g. Nordhaus, 2006), might be taken to argue that $\delta = 1.5\%$ and $\eta = 2$, while little or no account need be taken of risk or uncertainty. If we run the Stern Review's model with these assumptions, the total discounted cost of climate change is just 0.6%, too low to support strong action.

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[17] As is by now familiar in our sensitivity analyses, we consider the baseline-climate scenario, with market impacts, non-market impacts and the risk of abrupt, large-scale and discontinuous or 'catastrophic' climatic changes. PAGE2002 is comprehensively reported in Hope (2006).

[18] This measure of total discounted cost is derived from a comparison of the 'balanced growth equivalent' or BGE of consumption without climate change to the BGE of consumption after climate damage and adaptation costs have been deducted. It summarises simulated losses over time, regions of the world and possible states of the world in terms of a permanent loss of global mean per-capita consumption today.

If we revert to $\delta = 0.1\%$ and $\eta = 1$, so as to place more ethical weight on future generations again, but we continue to ignore risk and uncertainty, the mean estimated cost of BAU climate change is 3.5%, still well below the Stern Review's estimate. Symmetrically, if we assume $\delta = 1.5\%$ and $\eta = 2$, but take account of uncertainty by calculating expected utility, the cost of climate change is 1.1%. Neither ethics nor risk is alone sufficient to bridge the gap between the critics and ourselves. It is the interaction between the two that is crucial. This should be obvious: greater climate risks fall in the future, and it is only through affording future generations significant ethical weight that we would be motivated to protect them from these risks. Thus we believe it is an *error* to suggest that our results, which estimate damages that are higher than in most of the previous literature, come only from the different ethical parameters. They come, as we have insisted throughout the discussion, from a serious analysis of ethics, and from incorporating risk and analysis based on modern science. Much of the earlier economics literature has been remiss in its treatment of these key issues. Similarly, it is equally a conceptual mistake, in our view, to omit ethics from the discussion, arguing instead that climate-change mitigation is purely a question of risk management. The benefits of mitigation, in terms of risks avoided, accrue many decades and even centuries after the cost is paid. If anything, these risk management approaches can blur the ethical trade-offs.

What happens if we increase η, as for example Dasgupta (2006) has suggested, while at the same time placing more emphasis on the risk that climate change could inflict very high costs on growth and development, as for example Weitzman (2007) has encouraged. In Dietz *et al*. (2007b) we show that doing so, in effect combining the positions of some of the more thoughtful commentators, gives results similar to those of the central case of the Review.

We must emphasise very strongly, however, that the formal modelling we have presented still leaves out key issues that would raise estimated damages further. Among these issues, Sterner and Persson [citation] are quite right to highlight the importance of treating environmental goods as separate from other goods. This contrasts with the aggregated treatment of climate damages in almost all studies, including Chapter 6 of the Review. If incomes grow, but the environment is damaged due to BAU emissions, then the relative price of environmental goods, in terms of social willingness-to-pay, will rise sharply (see p58 of the Review). Thus, making alternative (non-mitigation) investments with the intent of 'buying down' climate damage later will very likely be a misguided policy. Sterner and Persson [citation] even show that, given certain assumptions about the share of environmental goods in human welfare, damages to these goods due to climate change, and substitutability between man-made and environmental capital, strong and urgent reductions in GHG emissions can be justified, despite a higher social discount rate. This perhaps represents an extreme case, where the risks of climate change to balanced economic development are so severe that action can be supported, without necessarily taking a position consistent with intergenerational equity. Weitzman (2007) presents an alternative thought experiment that leads to essentially the same conclusion.

5. Conclusions: act now or wait and see?

To keep things simple and focus on some analytical issues, we have so far effectively presented the policy problem in terms of a once-and-for-all decision on how much to abate GHG emissions. This is of course unrealistic and we must take into account the opportunities that decision-makers will have to adjust abatement effort, when new information comes to light on its costs and benefits. Indeed, there is an established and growing literature that investigates the timing of abatement and the relationship between short-term and long-term emission reductions, assuming that learning will resolve some of the uncertainties discussed above (see Ingham and Ulph, 2005; Fisher and Nackicenovic, 2007).

Nevertheless an understanding of the risks of action compared to the risks of inaction at the outset provides a benchmark to inform this approach. Central to the issues raised by future learning is whether and how much to reduce or delay making irreversible commitments today, in order to preserve the option of exploiting better information in the future. Whether the amount of abatement we undertake in the short term rises or falls in an analysis with learning, compared to an approach using a once-and-for-all decision with no learning, depends on the balance of at least three irreversibilities with different implications. (i) We risk an irreversible commitment to climate-change damages. All else equal, we would increase abatement in order to reduce this commitment. (ii) We risk an irreversible investment in capital that reduces GHG emissions. If we later discover that climate change is less of a threat, we will have needlessly invested in abatement capital, so the appropriate strategy now would be to undertake less abatement, all else equal. (iii) We risk an irreversible investment – lock-in – in energy- and carbon-intensive capital that produces GHG emissions, making delay in the achievement of a particular stabilisation target costly, having to make much more rapid reductions later. This is distinct from (i), which is an irreversibility in the physical system. It would lead us, all else equal, to increase abatement in the short term, in order to avoid lock-in to such capital, were climate change later to turn out to be a significant threat.

What is the appropriate hedging strategy is a question of attitudes towards risk and intertemporal values, types of learning that might occur, and an empirical question concerning different types of cost. Our central claim is that the risks of climate change, evaluated appropriately and in light of an explicit ethical discussion, make it much more important to avoid an irreversible commitment to climate change[19], linked to irreversible commitments to energy- and carbon-intensive capital in the next decade or two, than to avoid an irreversible commitment to abatement capital. This assumption underpins our conclusion that strong and urgent reductions in GHG emissions are required.

In doing so, the same structure of the risks points to setting a long-run quantitative goal for stabilising the atmospheric concentration of GHGs. The intuition behind this follows from Weitzman's (1974) seminal article on prices versus quantities. This has often been used to inform debates over taxation versus cap-and-trade as a policy instrument for GHG emission abatement in the short term. Here we reconsider it in the context of long-term emission reductions. Weitzman showed that quantity controls are the more efficient policy tool if the benefits of further reductions in pollution increase more with the level of pollution than do the costs of delivering these reductions (i.e., there are potentially large and sharply rising costs associated with exceeding a given level of pollution). We have argued that this is precisely the situation we are facing in climate-change policy over the long term. As the stock of GHGs rises, marginal damages are likely to rise, and as the stock reaches levels associated with dangerous warming (see section 4), marginal damages may rise steeply (i.e., there is strong convexity in the long-run marginal damage cost function). With time to adjust and with technical change, the marginal costs of abatement should by contrast be relatively flat.

As we explained in section 2, what stabilisation target we adopt should be informed by analyses such as Appendix 1 on the various distributions and dimensions of possible damages from climate change in different places and times, together with a mixture of formal and informal comparisons with analyses of the costs of stabilisation. The atmospheric stock of GHGs is currently around 430 ppm CO_2e and the rate of addition to that stock is around 2.5 ppm CO_2e per annum and rising quickly. This implies that delayed action will increase the stock to above 500 ppm in 25 years, making it very difficult to stay below 550 ppm. Appendix 1 shows that 550 ppm CO_2e is itself a risky place to be, with around a 50% probability that global average temperature increases will eventually exceed 3ºC relative to pre-industrial times, and a small chance that warming will eventually exceed 5ºC, a level where the risks of environmental, social and economic damages are very large indeed. Stabilisation above 550 ppm CO_2e clearly increases these risks. At 650 ppm CO_2e, Murphy *et al.* (2004) estimate that the probability of committing to an eventual temperature increase in excess of 5ºC is about 25%. Using Meinshausen's (2006) synthesis of 11 studies, it is 53%. At 750 ppm CO_2e, the respective probabilities from Murphy *et al*. and Meinshausen are 47% and 62%. It is very difficult to justify such a policy, as Mendelsohn tries to do in this symposium. On the other hand, since we have already reached around 430 ppm CO_2e,

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[19] We further assume that many of the risks of climate change can be avoided by abating greenhouse gas emissions, especially by stabilising at 450-550 ppm CO_2e.

stabilisation at anything significantly less than 450 ppm is likely to force firms into very costly adjustment, since they are working with fixed capital stocks and are restricted to currently available technologies.

Analysing the advantages and disadvantages of different targets suggests that the range should span 450 to 550 ppm CO_2e. In achieving a target within this range, an early commitment gives us the time to take measured action. Delay will be costly, creating a need for faster and deeper emission reductions in the future. As argued throughout this article, strong and urgent action is also likely to help reduce the cost of new, low-emission technologies more quickly, as there is substantial empirical evidence to show that deployment at scale triggers learning and economies of scale (IEA, 2000).[20] Furthermore, timely agreement on a long-run target range can boost the credibility of climate-change policy, stimulating even more investment in low-emissions techniques and technologies.

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[20] Central to the argument that strong action should be delayed, as suggested by Mendelsohn in this issue, is the notion that reductions in the cost of new technologies are ‘manna from heaven’ and are not affected by policy.

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Appendix 1. Stabilisation levels, probability ranges for temperature increases, and associated impacts on multiple dimensions. The top panel shows the range of temperatures projected at stabilisation levels between 400 ppm and 750 ppm CO_2e at equilibrium. The solid horizontal lines indicate the 5 – 95% range based on climate-sensitivity estimates from the IPCC *Third Assessment Report* of 2001 and Murphy *et al.* (2004). The vertical line indicates the mean of the 50th percentile point. The dashed lines show the 5 – 95% range based on eleven recent studies (Meinshausen, 2006). The bottom panel illustrates the range of impacts expected at different levels of warming.

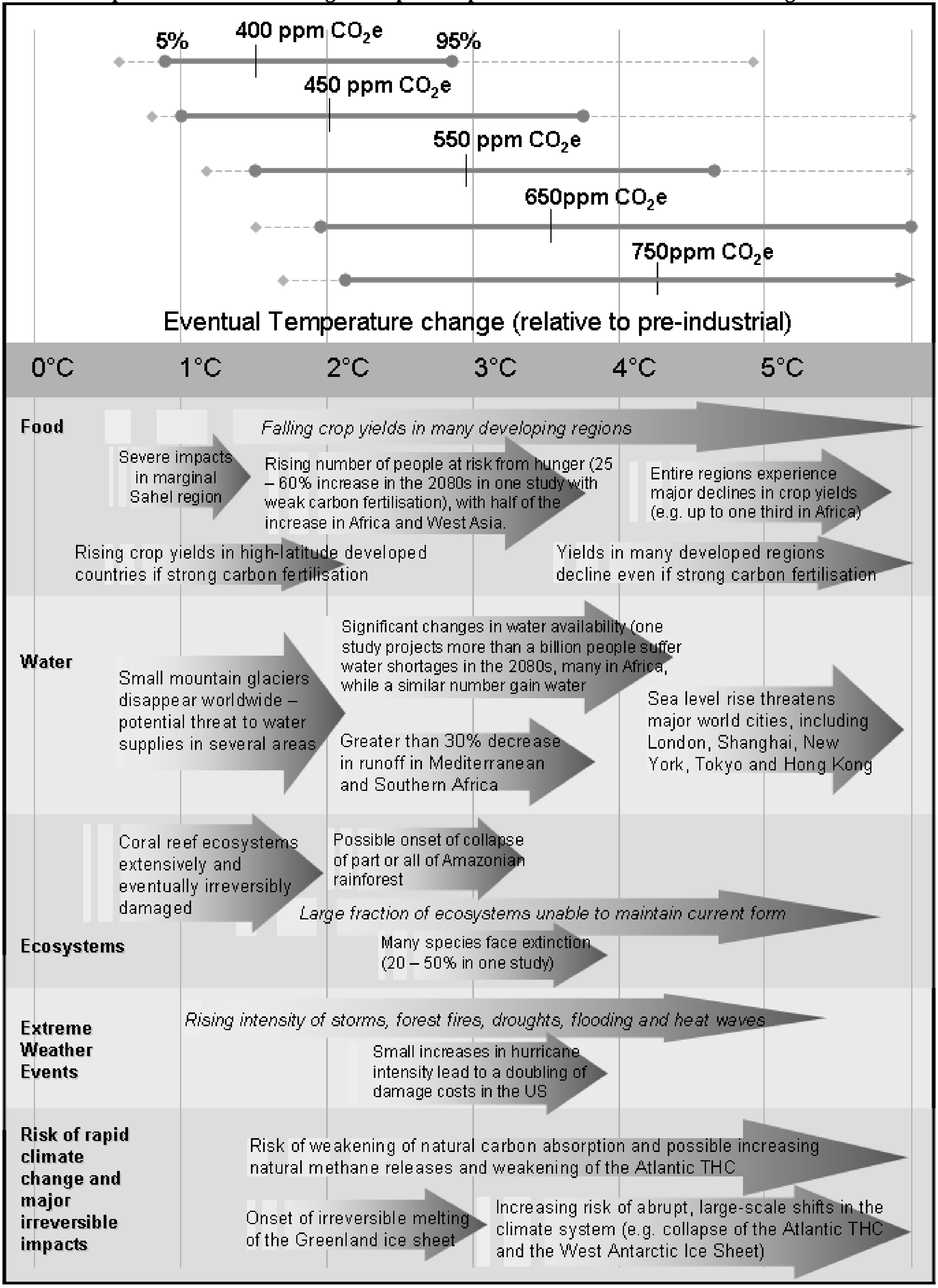

Figure 1. Comparison of estimates of climate sensitivity from three IAM studies and two ranges from the science. FUND 2.8 is an IAM study described in Tol (2006). DICE/RICE-99 is an IAM study described in Nordhaus and Boyer (2000). PAGE2002 is an IAM study described in Hope (2006) and is the IAM chosen for the Review's own modelling. "IPCC AR4 'likely' range" is taken from the *Fourth Assessment Report* of the IPCC (IPCC, 2007). It is a non-probabilistic range, where 'likely' denotes an expert judgement of a 66-90% likelihood. "Meinshausen 90%" is taken from Meinshausen (2006) and is the 5-95% confidence interval from eleven probability distributions reported in other studies.

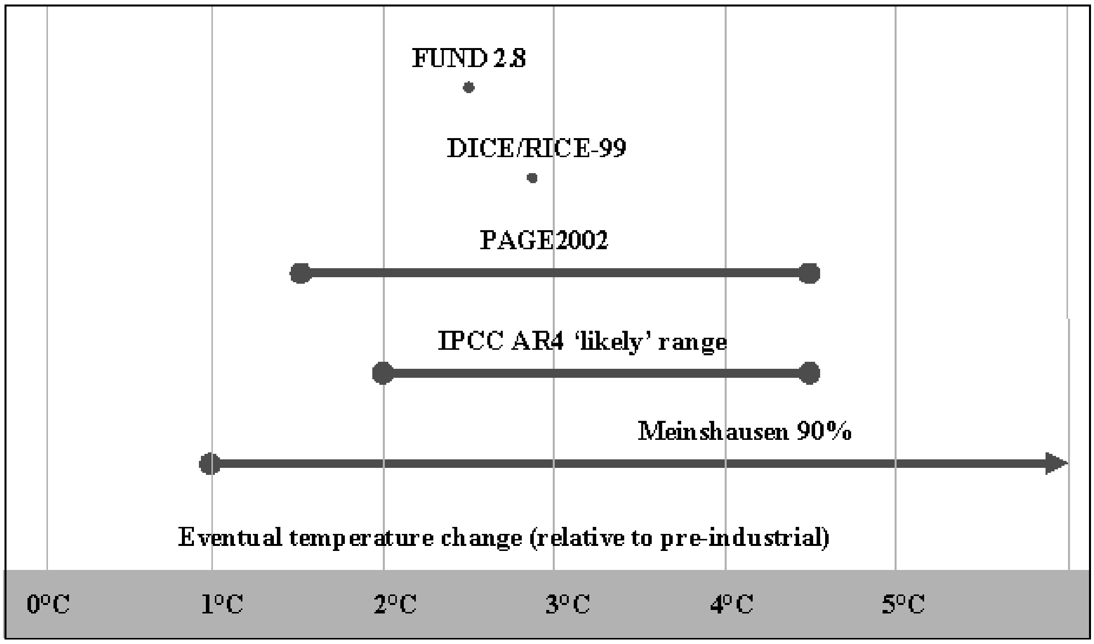

Figure 2. Comparing the dynamic costs of climate change, as a function of global mean temperature, estimated by leading IAMs (source: adapted from figure 6.2, p166, of Stern (2006), with original data from Smith *et al*., 2001).