Symposium:
The Economics of Climate Change: The *Stern Review* and Its Critics

Why Economic Analysis Supports Strong Action on Climate Change: A Response to the *Stern Review*'s Critics

Simon Dietz* and Nicholas Stern**

Introduction and Summary

Economic research that opposes the strategy of strong and urgent reductions in greenhouse gas (GHG) emissions, such as the articles in this symposium by Robert Mendelsohn (2008) and by John Weyant (2008), usually makes a distinction between scientists, environmentalists, politicians, and others who favor strong action, and economists, who apparently do not. Drawing on the *Stern Review on the Economics of Climate Change* (Stern 2007), this article 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[1] 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.

---

*Department of Geography and Environment and Centre for Environmental Policy and Governance, London School of Economics and Political Science (LSE), Houghton Street, London WC2A 2AE, UK; Tyndall Centre for Climate Change Research, University of East Anglia (UEA), Norwich, UK; e-mail: s.dietz@lse.ac.uk.
**London School of Economics and Political Science, London, UK.

We are grateful to Suzy Leonard, Robert Stavins, and one anonymous referee for useful comments on this paper, and to Dennis Anderson and Dimitri Zenghelis for a helpful discussion of the other papers in this symposium.

[1] 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).

Review of Environmental Economics and Policy, volume 2, issue 1, winter 2008, pp. 94–113
doi: 10.1093/reep/ren001
Advance Access publication on April 23, 2008

We begin 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 in the second section. Central to many critiques of the *Review*[2] is a fundamental misunderstanding of the role of formal, highly aggregated economic modeling in evaluating a policy issue that is characterized 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 judgments, and how they affect the scale and structure of policy. But to base real-world policy on the minimization of the present value of the costs of climate change and the costs of abating GHG emissions in a formal model—what Mendelsohn (2008) *equates* with "economic analysis"—is, we believe, 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 modeling 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 modeling structures, which are often chosen more for analytical convenience than anything else (Atkinson and Stiglitz 1980; Deaton and Stern 1986).

In the third and fourth sections, we review the nature of the risks and uncertainties surrounding the cost of emissions reductions versus the cost of business-as-usual (BAU) climate change. Mendelsohn (2008) suggests that we have overestimated the cost of climate change, on the one hand, and underestimated the cost of emissions reductions, on the other hand. Similarly, Weyant (2008) emphasizes that the cost of emissions reductions is uncertain. While we do not disagree with Weyant's observation, the key message of these sections is that the risks and uncertainties surrounding the impacts and costs of BAU climate change are much greater than those surrounding the costs of emissions 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 accept such risks (e.g., Mendelsohn 2008, 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. We believe that most people would find this conclusion unethical. Any discussion of discounting in the economics of public policy must include a discussion of intertemporal values. Thus, in the fourth section, we contend that ethics should be at the heart of the economic analysis and the consequences of using different intertemporal values explored and clarified. Moreover, we argue 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 emissions reductions is indeed as low as now seems likely). We conclude our paper in the fifth section by explaining why a sensible approach to risk implies that this is precisely the wrong strategy

---

[2] For example, see Mendelsohn (2008) and Weyant (2008), as well as Dasgupta (2006); Neumayer (2007); Nordhaus (2006); Tol and Yohe (2006, 2007); and Weitzman (2007).

for addressing GHG emissions. 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.

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.[3] 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 following 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 nonmarginal to the future path of global growth and development.

Any analysis that avoids addressing these elements explicitly is using a conceptual and analytical framework that 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.

With these issues in mind, the *Review*'s assessment was built on three lines of investigation. The simplest and the 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

---

[3] With appropriate intertemporal assessment and still further strain on assumptions, over time this can be seen as minimizing the present-value sum of external costs and abatement costs (cf. Mendelsohn (2008), in this symposium).

paying an insurance premium equal to the cost of mitigation for a given path to stabilize 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 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, stylized 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 behavioral changes in the economy as a whole in determining the cost of mitigation. Thus, the second line of investigation in the *Review* examined 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 emissions reductions to another (e.g., moving from a stabilization 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 well-being and the environment (e.g., reduced risks of food and water shortages).[4] We summarized the consequences of different stabilization 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 summarized in Chapter 13. Thus, Mendelsohn (2008) is mistaken in suggesting that we compared the costs of BAU climate change with only "one, near-term aggressive abatement policy."[5]

The Cost of Mitigation and Its Uncertainties

The basic premise of this and the following section 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 a discussion of the cost of mitigation.

The main finding from the *Review*'s assessment of the cost of mitigation[6] is that the cost through time of keeping GHG emissions to a plausible pathway to stabilization of atmospheric

---

[4] The three lines of investigation are, of course, logically related in a formal sense, but they represent different approaches to the problem.

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

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

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 percent of global GDP through the end of this century. As carefully explained in Chapter 13, stabilization 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, Naucler, and Rosander (2007), the International Energy Agency (IEA 2006), and the IPCC (2007a) have reported similar central estimates and ranges. These ranges, though large, are still much narrower than the range one has to consider for the cost of climate change.

Stabilizing 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 stabilization 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 percent less than current levels (given growth of the global economy in the intervening years, they will have to be around 75 percent less per unit of GDP).[7] To stabilize 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 percent 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 stabilization 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 stabilization (e.g., Pacala and Socolow 2004).[8] Moreover, further research and development should broaden and deepen that set.

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-emissions technologies), the increase in cost seems manageable. Roughly 40 percent of the global emissions derive from nonfossil fuel sources, and here reductions could be won at a low cost. One example is avoiding deforestation, which could cost less than \$5 per metric 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).[9] Another source of emissions reductions is improvements in energy efficiency. As the International Energy Agency's studies (e.g., IEA 2006) have

---

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

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

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

highlighted, there is considerable technical potential for energy efficiency to deliver emissions 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 come mainly from the need to deploy some mix of low-emissions 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 current costs of such technologies are higher than incumbent high-emissions technologies, but not by the orders of magnitude that would truly send the costs of stabilization skyrocketing (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-emissions 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-emissions 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 behavioral linkages and thus of simulating, for example, substitutions from high-emissions to low-emissions 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 behavior, technologies, and policy that can be difficult to decipher (making the meta-analyses of Fischer and Morgenstern 2005; and Barker, Qureshi, and Koehler 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, summarized in the *Review* as a range of ±3 percent of GDP. Weyant (2008) argues that the range is wider, up to 10 percent of GDP. However, we do not consider the high end of this range to be credible, as these estimates apparently originate from modeling studies that treated technical change unrealistically (by ignoring either the possibility of a backstop technology[10] or possibilities to substitute away from high-emissions 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 emphasize, flexible policy (in terms of where and when emissions 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. In order to assess the likely costs of mitigation in a world where behavioral 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 behavioral modeling exercises. It showed that under

---

[10] 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.

a *feasible* technology mix,[11] replacing carbon-intensive energy generation and transportation with low-carbon technologies to stabilize at 550 ppm CO_2e could be attained at a mean cost of approximately 1 percent 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 behavioral models, this approach offered a very simple and transparent way of making a first approximation of the likely cost of one route to stabilization. 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 (2008) in this symposium. Assume that stabilization at 550 ppm CO_2e requires global emissions 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, stabilization at 550 ppm CO_2e would cost \$4 trillion by 2050, or about 3.6 percent of global GDP.[12] Now ask how high the average cost of abatement would have to be if we assume Weyant (2008) is correct in putting the upper end of the range of likely stabilization costs at 10 percent of GDP. The answer using simple arithmetic is \$1000/tCO_2. The vast majority of low-emissions technologies is 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.

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.

---

[11] Not an *optimal* mix. Some critiques of this part of the *Review*, such as Mendelsohn's in this symposium, are wide of the mark, because they mistakenly assume that (1) Anderson (2006) explored just one pathway (he explored thousands in a Monte Carlo analysis), and (2) that any one of these pathways is the one actually advocated by the *Review*.

[12] In contrast, Mendelsohn's calculations assume that (1) the average cost of abatement estimated by the *Review* is \$400 per metric tonne of carbon, and (2) stabilization at 550 ppm CO_2e requires emissions 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 percent of GDP. But closer inspection reveals that he (1) mistakes the average cost per *tonne* of carbon for the average cost per *tonne* of CO_2, which inflates any estimate by a factor of 3.7, and (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.

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 emissions 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 5°C warming or more (Murphy et al. 2004; Meinshausen 2006; IPCC 2007b). A change of 5°C is comparable to the difference between temperatures today and temperatures 10,000–12,000 years ago, when most of Northern Europe and North America were under hundreds of meters of ice. A further 5°C increase would transform 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 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, which would eventually contribute meters to global sea levels. It is not at all 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, b), 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 modeling 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.

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 "nonmarket" impacts, because no market prices exist) are omitted. Other IAMs, such as Tol's (2002) assessment, include a wide range of market and nonmarket impacts, but are restricted to gradual climate change. Such studies do not consider the possibility of abrupt, large-scale, and discontinuous climatic changes, which recent climate science has identified (e.g., Schellnhuber et al. 2006).

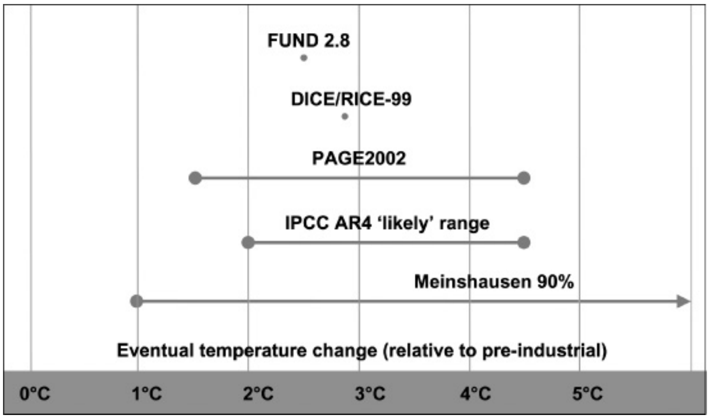


Figure 1. Comparison of estimates of climate sensitivity from three IAM studies and two ranges from the science. FUND 2.8 is an IAM study described in Tol (2006). DICE/RICE-99 is an IAM study described in Nordhaus and Boyer (2000). PAGE2002 is an IAM study described in Hope (2006) and is the IAM chosen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

In fact, *none* of the IAMs formally incorporate 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 only make a "best guess" at how much warming will occur. 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 2–3°C this century. Such a forecast is too sanguine, because climate science tells us to consider more rapid warming (see IPCC 2007b, which projects up to 6.4°C 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 1°C warming (see Schneider and Lane 2006), although they consider only the physical process, not its social and economic impacts.

In the *Review*, we chose to carry out some of our own modeling, 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 center of the range of estimates produced by other models (see Figure 2). Thus, contrary to the impression some critics may have created (e.g., Byatt et al. 2006; Mendelsohn (2008)), the *Review*'s modeling is not inconsistent with the underlying literature in its quantification

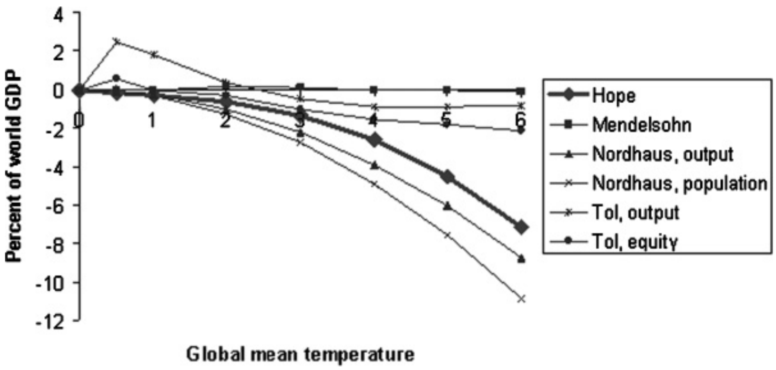


Figure 2. Comparing the dynamic costs of climate change, as a function of global mean temperature, estimated by leading IAMs.
Source: Adapted from Figure 6.2, p. 166, of Stern (2007), with original data from Smith et al. (2001).

of the cost of climate change.[13] Where it does differ from the literature is, first, in formally modeling a wider range of possible temperature changes, and second, in explicitly modeling aversion to the most severe climate risks.

To explain the latter point, we must recognize that all the links in the chain between GHG emissions and the economic impacts of climate change—each of which needs to be parameterized in an IAM—are of course subject to uncertainty. But most previous studies have failed to tackle this uncertainty. The simplest modeling 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 Monte Carlo procedure, enabling climate impacts to be modeled probabilistically (e.g., Plambeck, Hope, and Anderson 1997; Roughgarden and Schneider 1999; Mastrandrea and Schneider 2004; Hope 2006). Yet very few of these studies extend to an application of expected-utility analysis (exceptions are Tol 1999, 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.

---

[13] We suspect that Mendelsohn (2008) has confused 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 *Review*'s estimates of the cost of extreme weather events. We have no idea, however, where in the *Review* he has found an estimate of the cost of extreme weather events that is 5 percent 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).

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.[14] Still, the structure of risks included in the *Review*'s formal modeling should be seen as *cautious* (figure 1 is an intuitive illustration of this), indeed perhaps too cautious (see Weitzman 2007). However, the scenarios and parameter values chosen are within the ranges established in the existing literatures, and it is these existing literatures that constrain the ability of the modeling to keep pace with newly emerging risks.

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 2008 and Weyant 2008 in this symposium, as well as Dasgupta 2006, Nordhaus 2006, and Weitzman 2007). We believe it is a mistake, however, 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 prespecified path of economic growth. In the case of climate change, we must take account of the risk of economic effects that are nonmarginal to the future path of global growth and development. That is, the risks of climate change mean that we cannot assume that 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.

Even within a standard, medium-term benefit-cost 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 the benefits of 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 (2008), 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 center stage.

In formal economic modeling, 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

---

[14] 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*.

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 Equation (1) has a different role. First, in this framework, η captures attitudes not only toward intergenerational distribution, but also toward risk and intragenerational 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 are not aware of any serious ethical argument in favor of extreme values of δ of 2 percent or 3 percent 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 be understood largely 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.[15] When interpreted as discrimination by birth date, extreme values of δ are difficult to justify. For example, 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 by the one born in 2007 would be given only half the weight of an extra unit of consumption by 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 minimize short-term mitigation costs, passing the burden on to the next generation.

Next, we examine growth, g. The growth assumptions in the formal modeling of Chapter 6 of the *Review* were fairly conservative: global growth starts at around 2.5 percent on aggregate (0.9 percent per capita, due to rapid population growth) and falls to around 1.8 percent (1.4 percent per capita) in the latter half of the twenty-second 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 modeled these effects, but our judgment and preliminary assessments suggest that both effects are strong. Third, faster growth could increase adaptive capacity,

---

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

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 for η? Many benefit-cost 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 (2008)). To illustrate, let us 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 prepared to lose along the way, for example, through administrative costs? Those who argue that $\eta = 2$ 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 percent 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 recognize 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 recognize 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 implies 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, is consistent with current rates of savings.

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 b). In the *Stern Review*'s base modeling case,[16] we set $\delta = 0.1$ percent per annum and $\eta = 1$, and we took risk into account by calculating expected utility from a wide range of scenarios. The resulting present value of the cost of climate change was equivalent to a 10.9 percent loss in global mean per capita consumption.[17] Previous studies, as well as some critiques of our formal modeling (e.g., Nordhaus 2006), might be taken to argue that $\delta = 1.5\%$ and $\eta = 2$,

---

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

[17] 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

and that 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 percent, too low to support strong action.

If we revert to $\delta = 0.1\%$ and $\eta = 1$, so as to again place more ethical weight on future generations, but we continue to ignore risk and uncertainty, the mean estimated cost of BAU climate change is 3.5 percent, still well below the *Stern Review*'s estimate. Symmetrically, if we assume that $\delta = 1.5\%$ and $\eta = 2$, but take account of uncertainty by calculating expected utility, the cost of climate change is 1.1 percent. 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, in our view, it is a conceptual mistake 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 may 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 suggested? In Dietz et al. (2007b), we show that doing so gives results similar to those of the central case of the *Review*.

We must emphasize very strongly, however, that the formal modeling we have presented still leaves out key issues that would raise estimated damages further. Among these issues, Sterner and Persson (2008) 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 p. 58 of the *Review*). Thus, making alternative (nonmitigation) investments with the intent of "buying down" climate damage later will very likely be a misguided policy. Sterner and Persson (2008) 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 even with a higher social discount rate. However, this may represent an extreme case, in which the risks of climate change to balanced economic development are so severe that strong and urgent action can be supported, but without necessarily taking a position consistent with

---

adaptation costs have been deducted. It summarizes 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.

intergenerational equity. Weitzman (2007) presents an alternative thought experiment that leads to essentially the same conclusion.

Conclusions: Act Now or Wait and See?

In order to keep things simple and to focus on some analytical issues, we have thus far 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 the 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 emissions reductions, assuming that learning will resolve some of the uncertainties discussed above (see Ingham and Ulph 2005; Fisher et al. 2007).

Nevertheless, an understanding at the outset of the risks of action compared to the risks of inaction provides a benchmark to inform the approach presented in this literature. 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. In an analysis with learning, the amount of abatement we undertake in the short term, compared to an approach using a once-and-for-all decision with no learning, depends on the relative importance of at least three irreversibilities, each with different implications: (i) We risk an irreversible commitment to climate change damages. In this case, 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. In this case, if we later discover that climate change is less of a threat, we will have needlessly invested in abatement capital. This means, all else equal, the appropriate strategy would now be to undertake less abatement. (iii) We risk an irreversible (i.e., locked-in) investment in energy- and carbon-intensive capital that produces GHG emissions, making delay in the achievement of a particular stabilization target costly because we will have 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 being locked in to such capital should climate change turn out later to be a significant threat.

The appropriate hedging strategy depends on attitudes toward risk and intertemporal values, types of learning that might occur, and empirical questions concerning different types of cost. Our central claim is that when the risks of climate change are evaluated appropriately and in light of an explicit ethical discussion, it becomes much more important to avoid an irreversible commitment to climate change,[18] which is 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 is the assumption that underpins our conclusion that strong and urgent reductions in GHG emissions are required.

The same structure of risks points to setting a long-run quantitative goal for stabilizing 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

---

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

over using 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 emissions reductions. Weitzman showed that quantity controls are the more efficient policy tools 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 the fourth section), marginal damages may rise steeply (i.e., there is a 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 the second section, what stabilization target we adopt should be informed by analyses of the various distributions and dimensions of possible damages from climate change in different places and times (see Appendix 1), together with a comparison of formal and informal analyses of the costs of stabilization. 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-percent probability that global average temperature increases will eventually exceed 3°C relative to preindustrial times, and a small chance that warming will eventually exceed 5°C, a level where the risks of environmental, social, and economic damages are very large indeed. Stabilization 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 5°C is about 25 percent. Using Meinshausen's (2006) synthesis of eleven studies, it is 53 percent. At 750 ppm CO_2e, the respective probabilities from Murphy et al. and Meinshausen become 47 percent and 62 percent, respectively. 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, stabilization 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.

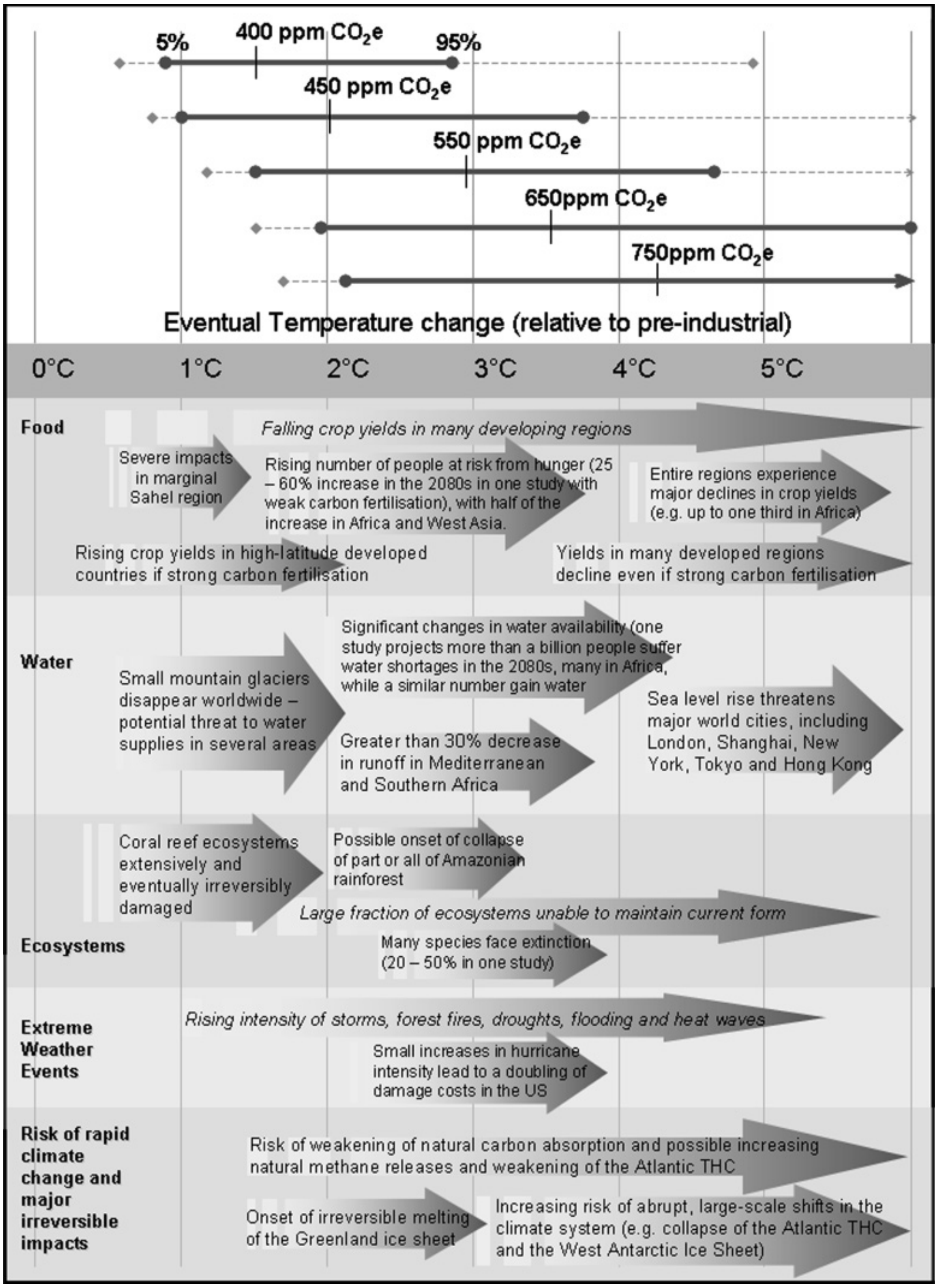
Analyzing the advantages and disadvantages of different stabilization targets suggests that the range should span 450 to 550 ppm CO_2e. If we are to achieve a target within this range, an early commitment gives us the time to take measured action. Delay will be costly, creating a need for faster and deeper emissions reductions in the future. As argued throughout this article, strong and urgent action is also likely to help reduce the cost of new, low-emissions technologies more quickly, as there is substantial empirical evidence to show that deployment at scale triggers learning and economies of scale (IEA 2000).[19] 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.

---

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

Appendix I

Stabilization levels, probability ranges for temperature increases, and associated impacts on multiple dimensions. The top panel shows the range of temperatures projected at stabilization levels between 400 ppm and 750 ppm CO_2e at equilibrium. The solid horizontal lines indicate



the 5–95 percent 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 percent range based on eleven recent studies (Meinshausen 2006). The bottom panel illustrates the range of impacts expected at different levels of warming.

References

Anderson, D. 2006. Costs and finance of carbon abatement in the energy sector. Paper prepared for the *Stern Review*.

Atkinson, A. B., and J. E. Stiglitz. 1980. *Lectures on Public Economics*. London: McGraw-Hill.

Azar, C., and T. Sterner. 1996. Discounting and distributional considerations in the context of global warming. *Ecological Economics* 19(2): 169–84.

Barker, T., M. S. Qureshi, and J. Koehler. 2006. *The Costs of Greenhouse-Gas Mitigation with Induced Technological Change: A Meta-Analysis of Estimates in the Literature*. Cambridge: Cambridge Centre for Climate Change Mitigation Research (4CMR), University of Cambridge.

Byatt, I., I. Castles, I. M. Goklany, D. Henderson, N. Lawson, R. McKitrick, J. Morris, A. Peacock, C. Robinson, and R. Skidelsky. 2006. The *Stern Review*: A dual critique. Part II: Economic aspects. *World Economics* 7(4):195–229.

Cline, W. R. 1992. *The Economics of Global Warming*. Washington, DC: Institute for International Economics.

Dasgupta, P. 2006. Comments on the *Stern Review*'s Economics of Climate Change. Cambridge: University of Cambridge.

Deaton, A., and N. Stern. 1986. Optimally uniform commodity taxes, taste differences, and lump-sum grants. *Economics Letters* 20(3):263–66.

Dietz, S., C. Hope, N. Stern, and D. Zenghelis. 2007a. Reflections on the *Stern Review* (1): A robust case for strong action to reduce the risks of climate change. *World Economics* 8(1):121–68.

Dietz, S., D. Anderson, N. Stern, C. Taylor, and D. Zenghelis. 2007b. Right for the right reasons: A final rejoinder on the *Stern Review*. *World Economics* 8(2):229–58.

Downing, T. E., D. Anthoff, B. Butterfield, M. Ceronsky, M. Grubb, J. Guo, C. Hepburn, et al. 2005. *Scoping Uncertainty in the Social Cost of Carbon*. London: DEFRA.

Ellsberg, D. 1961. Risk, ambiguity, and the Savage axiom. *Quarterly Journal of Economics* 75(4):643–69.

Enkvist, P.-A., T. Naucler, and J. Rosander. 2007. A cost curve for greenhouse gas reduction. *The McKinsey Quarterly* 2007(1):35–45.

Fischer, C., and R. D. Morgenstern. 2005. Carbon abatement costs: Why the wide range of estimates? *Discussion Paper 03–42*. Washington, DC: Resources for the Future.

Fisher, B. S., N. Nakicenovic, K. Alfsen, J. Corfee Morlot, F. de la Chesnaye, J.-C. Hourcade, K. Jiang, et al. 2007. Issues related to mitigation in the long-term context. In *Climate Change 2007: Mitigation*, ed. B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, and L. A. Meyer. Contribution of Working Group III to the Fourth Assessment Report of the Inter-Governmental Panel on Climate Change. Cambridge and New York: Cambridge University Press, pp. 169–250.

Grieg-Gran, M. 2006. The cost of avoiding deforestation. Report prepared for the *Stern Review*. London: International Institute for Environment and Development.

Hepburn, C. J. 2006. Discounting Climate Change Damages: Working Note for the *Stern Review*.

HM Treasury. 2003. *The Green Book: Appraisal and Evaluation in Central Government: Treasury Guidance*. London: Stationery Office.

Hope, C. 2006. The marginal impact of CO_2 from PAGE2002: An integrated assessment model incorporating the IPCC's five reasons for concern. *Integrated Assessment Journal* 6(1):19–56.

IEA. 2000. *Experience Curves for Energy Technology Policy*. Paris: OECD/IEA.

———. 2006. *World Energy Outlook 2006*. Paris: OECD/IEA.

Ingham, A., and A. Ulph. 2005. Uncertainty and climate-change policy. In *Climate-Change Policy*, ed. D. Helm. Oxford: Oxford University Press, pp. 43–72.

IPCC. 2007a. *Climate Change 2007: The Physical Science Basis: Summary for Policymakers*. Geneva: IPCC.

———. 2007b. *Climate Change 2007: The Physical Science Basis: Summary for Policymakers*. Geneva: IPCC.

Kahneman, D., and A. Tversky. 1979. Prospect theory: An analysis of decision under risk. *Econometrica* 47:263–91.

Knight, F. H. 1921. *Risk, Uncertainty, and Profit*. Boston, MA: Houghton Mifflin.

Mastrandrea, M. D., and S. H. Schneider. 2004. Probabilistic integrated assessment of "dangerous" climate change. *Science* 304:571–75.

Meinshausen, M. 2006. What does a 2 deg C target mean for greenhouse gas concentrations? A brief analysis based on multi-gas emission pathways and several climate sensitivity uncertainty estimates. In *Avoiding Dangerous Climate Change*, ed. H.-J. Schellnhuber, W. Cramer, N. Nakicenovic, T. Wigley, and G. Yohe. Cambridge: Cambridge University Press.

Mendelsohn, R. O. 2008. Is the *Stern Review* an economic analysis? *Review of Environmental Economics and Policy*. doi: 10.1093/reep/rem023.

Mendelsohn, R. O., W. N. Morrison, M. E. Schlesinger, and N. G. Andronova. 1998. Country-specific market impacts of climate change. *Climatic Change* 45(3–4):553–69.

Murphy, J. M., D. M. H. Sexton, D. N. Barnett, G. S. Jones, M. J. Webb, and M. Collins. 2004. Quantification of modeling uncertainties in a large ensemble of climate change simulations. *Nature* 430(7001): 768–72.

Neumayer, E. 2007. A missed opportunity: The *Stern Review* on climate change fails to tackle the issue of non-substitutable loss of natural capital. *Global Environmental Change* 17(3–4):297–301.

Nordhaus, W. D. 2006. The *Stern Review* on the economics of climate change. National Bureau of Economic Research Working Paper No. 12741. Cambridge, MA: National Bureau of Economic Research.

Nordhaus, W. D., and J. Boyer. 2000. *Warming the World: Economic Models of Global Warming*. Cambridge, MA: MIT Press.

Pacala, S., and R. Socolow. 2004. Stabilization wedges: Solving the climate problem for the next 50 years with current technologies. *Science* 305(5686):968–72.

Plambeck, E. L., C. Hope, and J. Anderson. 1997. The PAGE95 model: Integrating the science and economics of global warming. *Energy Policy* 19:77–101.

Roughgarden, T., and S. H. Schneider. 1999. Climate change policy: Quantifying uncertainties for damages and optimal carbon taxes. *Energy Policy* 27:415–29.

Schellnhuber, H. J., W. Cramer, N. Nakicenovic, T. Wigley, and G. W. Yohe. 2006. *Avoiding Dangerous Climate Change*. Cambridge: Cambridge University Press.

Schneider, S. H., and J. Lane. 2006. *An Overview of "Dangerous" Climate Change. Avoiding Dangerous Climate Change*, ed. H. J. Schellnhuber, W. Cramer, N. Nakicenovic, T. Wigley, and G. W. Yohe. Cambridge: Cambridge University Press, pp. 7–23.

Smith, J. B., H.-J. Schellnhuber, and M. M. Q. Mirza. 2001. Vulnerability to climate change and reasons for concern: a synthesis. Climate Change 2001: Impacts, Adaptation, and Vulnerability: Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. J. J. McCarthy, O. F. Canziani, N. A. Leary, D. J. Dokken and K. S. White, 913–967. Cambridge: Cambridge University Press.

Stern, N. 2007. *The Economics of Climate Change: The Stern Review*. Cambridge: Cambridge University Press.

Sterner, T., and U. M. Persson. 2008. An even Sterner *Review*: Introducing relative prices into the discounting debate. *Review of Environmental Economics and Policy*. doi: 10.1093/reep/rem024.

Tol, R. S. J. 1999. Safe policies in an uncertain climate: An application of FUND. *Global Environmental Change* 9:221–32.

———. 2002. Estimates of the damage cost of climate change—Part II: Dynamic estimates. *Environmental and Resource Economics* 21:135–60.

———. 2003. Is the uncertainty about climate change too large for expected cost-benefit analysis? *Climatic Change* 56:265–89.

———. 2006. The benefits of greenhouse gas emission reduction: An application of FUND. Stern Review, "What is the Economics of Climate

Change?" Discussion Paper Responses.

Tol, R. S. J., and G. W. Yohe. 2006. A review of the *Stern Review. World Economics* 7(4): 233–50.

———. 2007. A Stern reply to the reply to the review of the *Stern Review. World Economics* 8(2):153–59.

Warren, R., C. Hope, M. Mastrandrea, R. Tol, N. Adger, and I. Lorenzoni. 2006. Spotlighting impacts functions in integrated assessment: Research report prepared for the *Stern Review* on the Economics of Climate Change.Tyndall Centre for Climate Change Research Working Paper No. 91.

Weitzman, M. L. 1974. Prices versus quantities. *Review of Economic Studies* 41(4):477–91.

———. 2007. The *Stern Review* of the economics of climate change. *Journal of Economic Literature* 45(3):703–24.

Weyant, J. P. 2008 A critique of the *Stern Review*'s mitigation cost analyses and integrated assessment. *Review of Environmental Economics and Policy*. doi: 10.1093/reep/rem022.