Nordhaus, Stern, and Garnaut: The Changing Case for Climate Change Mitigation

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Abstract

Today the idea that climate change requires a gradual and moderate response no longer commands consensus support among economists. A more demanding approach is gaining ground. This paper traces the changes in economic thinking concerning the case for action on climate change, through an analysis of the work of three eminent economists: William Nordhaus, Nicholas Stern and Ross Garnaut. It shows how from Nordhaus to Stern to Garnaut the case for more urgent and radical mitigation has been strengthened as temperature targets have been lowered and business-as-usual emissions projections raised. It also shows that Stern and especially Nordhaus, who has been working on this subject the longest, have changed their own views in favour of more urgent and radical mitigation. Some disagreements remain between these three economists, and some other economists have more moderate views, but the old consensus has been shattered.

1. Introduction

In 1999, Kelly and Kollstad (cited by Nordhaus 2008, p. 216) summarized the consensus among climate change modellers as it then stood: "modest controls are generally optimal." Today, however, the idea that climate change requires a gradual and moderate response no longer commands widespread support among economists. A more demanding approach, favouring a more ambitious target and supporting more urgent action, is gaining ground.

This paper traces the changes in economic thinking concerning the case for action on climate change. We tell that story by analysing the work of three eminent economists: William Nordhaus, Nicholas Stern, and Ross Garnaut.

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All errors are our own.

William Nordhaus is a renowned pioneer in the economic analysis of global climate change. His work, which traces back to the 1970s, exemplifies the early consensus which Kelly and Kollstad synthesize. In his 2000 book with Joseph Boyer*, Warming the World: economic models of global warming*, Nordhaus presents an optimal policy scenario in which industrial emissions of carbon dioxide (CO_2) are nearly double at the end of the century compared to their level at the start (Nordhaus and Boyer 2000, Table 7.7). Average global temperatures increase to around 2.4°C above pre-industrial levels by the end of this century, on a rising trajectory to a maximum of 4.4 °C.

Nicholas Stern was not the first to challenge the prevailing consensus among economists in favour of moderate and delayed mitigation (for example, see Cline 1992), but he was certainly the most prominent and influential. In his 2007 Review, commissioned by the UK Labour Government, Stern bucked the consensus among economists that a 3-degree target[2] was the lower bound for efficient mitigation (Tol and Yohe 2008, p. 240). He advocated instead a 2-3 degree target range (Stern 2007, p. 338). Not only did Stern support a more ambitious target, but he argued for "strong action now" (Stern 2007, p. xv). Stern's work had an immense and immediate impact, not least in unleashing a debate which, in the process of challenging Stern's results, helped change the way in which economists thought about climate change.

Ross Garnaut reported to Australia's Federal and state governments in 2008 on the national case for climate change mitigation. The Garnaut Review had the advantage of being written in the aftermath of the Stern debate, and was therefore able to address the issues that had emerged from it. Garnaut's analysis was also one of the first to recognize that most projections had underestimated the growth of future emissions absent mitigation. This made the job of mitigation more difficult, but despite this the Garnaut Review proposed an even more ambitious global target than Stern – not a 2-3 degree range, but a 2-degree target (Garnaut 2008, p. 272).

The next three sections delve into the analysis of each of these three authors. It would be misleading, however, only to present this debate about how much to mitigate simply in

[2] We use 'temperature target' as a short hand for 'limit on the extent to which temperatures should be allowed to rise'. All temperature increases are relative to pre-industrial levels unless otherwise specified.

these linear, consecutive terms. Rather, the debate was conducted against a shifting scientific consensus, which over time elevated the risks from climate change. And all three of the authors we focus on were participants in and were influenced by the post-Stern Review debate. Section 5 looks at the more recent views expressed by Stern and Nordhaus, and makes the case for an emerging consensus.

This paper is not intended as a comprehensive review and critique of any of the three authors, let alone of the normative economics literature on global climate change action. We do, however, make reference to the broader literature; especially in the conclusion where we show the divide among economists which now exists.

A recent paper by Smith (2011) provides a useful comparison of the work of the same three authors. Smith's focus is on the authors' treatment of uncertainty and discounting, and their implications for the target temperature range. We also examine the assumptions of the three authors about business as usual emissions projections and how these also influence the case for action. The present study also gives greater consideration to the evolution of views over time, and places more emphasis on the common ground between the three authors, at least with respect to their most recent work. On the other hand, Smith puts Stern and Garnaut in the "strong and early action" camp and Nordhaus in the "weaker and more gradual" camp (Smith 2011, p. 1).

2. William Nordhaus

In this section, we focus primarily on Nordhaus and Boyer (2000). Section 5 examines the author's more recent work, both Nordhaus (2008) and Nordhaus (2010).

Nordhaus estimates the costs and benefits of climate change using an integrated assessment model (IAM), which attempts to capture the key geophysical and economic dimensions of climate change through a system of mathematical equations.[3] The benefit of

[3] See Chapters 2, 3 and 4 of Nordhaus and Boyer (2000), and Nordhaus (2008, pp. 30-64) for a detailed description of this modelling procedure and underlying assumptions. Nordhaus has actually used two

this approach is that it permits the identification of an optimal emissions trajectory across time from an infinite number of possible trajectories. The major cost is simplification of the complexities inherent to the climate system into a structure amenable to economic modelling. For example, the costs of climate change are represented by a smooth damage function (Nordhaus and Boyer 2000, p. 4.48). Only industrially produced CO_2 is considered endogenous. Other greenhouse gas emissions, such as CO_2 from land-use change and methane, are treated as exogenous (Nordhaus and Boyer 2000, p. 3.21).

The moderate degree of mitigation supported by Nordhaus' analysis is demonstrated by comparing his no-mitigation outcomes with those of his optimal mitigation strategy. Under the no-mitigation scenario, CO_2 concentrations rise from 365 ppm in 2005 to 573 ppm in 2105 (Nordhaus 2000).[4] Global mean temperatures rise to 2.5 degrees Celsius above pre-industrial levels over the same period (Nordhaus and Boyer 2000, p. 7.31). Under the optimal policy strategy, CO_2 concentrations and average global temperatures respectively increase to 551 ppm (Nordhaus 2000) and 2.4°C (above pre-industrial levels) by 2105 (Nordhaus and Boyer 2000, p. 7.31). Looking forward two centuries, optimal emissions and temperatures peak at 830 ppm and 4.4°C respectively, not far below the no-mitigation maxima of 884 ppm and 4.6 °C (Nordhaus 2000).

If one general feature of Nordhaus' work has been a relatively high ultimate temperature (and concentration) target, the other has been his advocacy of a moderate start to mitigation. This position, another important part of the pre-Stern consensus, is known as the 'policy ramp'. This is the argument that the optimal response to climate change involves "modest rates of emissions reductions in the near term, followed by sharp reductions in the medium and long terms" (Nordhaus 2008, p. 14). Nordhaus and Boyer's (2000) optimal

related IAMs throughout his work: RICE, which is more complicated and divides the world into regions, and DICE, which runs purely at a global level and, in earlier versions, is more capable of handling longer timeframes. Nordhaus calibrates DICE so that the major results (such as temperature rise) and underlying relationships (such as the damage function) are largely as per RICE (see Nordhaus and Boyer 2000, Chapter 5). In the following we follow the authors' directions (Nordhaus and Boyer 2000, p. 4.7) and use DICE for the 2000 modelling beyond the 21st century, as well as any 21st century results not found in the text. Apart from this, unless specified otherwise, we refer to results and data associated with the major model used in the different analyses, namely: DICE for Nordhaus (2008), and RICE for Nordhaus and Boyer (2000) and Nordhaus (2010).

4 In Nordhaus and Boyer (2000), concentrations are expressed in GtC. We convert to ppm using the conversion factor 1 ppm=2.13 GtC.

policy run involves emissions at the end of the century being twice as high as they are at the start, and only 11% below business as usual (Nordhaus and Boyer 2000, p. 7.29).

Nordhaus' support for moderate and staggered mitigation is also evident from the optimal global carbon price which emerges from his modelling. This started as low as US$2.40 (2005 prices) per tonne of CO_2 in his 2000 work.[5]

These results are typical of other early economic analyses that recommended minimal and delayed emissions abatement.[6] Tol (1997) found that optimal mitigation diminishes global warming by 2100 from around 4°C above 1990 levels to between 3.6°C and 3.9°C. Likewise, Manne and Richels (1995) identified an optimal strategy that reduces atmospheric concentrations of carbon dioxide from around 800 ppm in 2100 to approximately 750 ppm.

A principal reason for the moderate mitigation recommended by these earlier studies is that climate change simply did not figure as a major economic risk at a global scale. A striking feature of Nordhaus' analysis is that even quite high levels of climate change are typically assumed to cause limited economic damages. Although some regions are much more greatly affected than others in his 2000 work (see Nordhaus and Boyer 2000, p. 4.49), the aggregate impact is minimal. Under the no-mitigation scenario (i.e. a world of unmitigated climate change), the damages associated with 2.6°C warming by 2105 and 3.9°C by 2205 are respectively estimated to be only about 1.4% and 3.5% of global Gross Domestic Product (GDP) (Nordhaus 2000).[7]

Figure 1 compares Nordhaus' figures for global GDP in a world of no climate change and one of unmitigated climate change. There is very little difference between the two scenarios this century, and even the next two. Climate change does not emerge from Figure 1 as a game-

[5] Present authors' conversion of Nordhaus' US$ 5.9 (1990 levels) per tonne of carbon figure (Nordhaus and Boyer 2000, p. 7.28)

[6] See Stern (2007, p. 338) for a review of these earlier works from which this paragraph draws.

[7] To aggregate regional damages in the RICE model Nordhaus weights either population or output to obtain a global estimate. This produces different results (see Nordhaus and Boyer 2000, p. 4.48). To avoid picking one over the other, we simply use the DICE estimates which are very similar in form (Nordhaus and Boyer 2000, p. 5.3). This also allows comparison with Nordhaus' later work further on in this section.

changer for the world economy, let alone an existential threat. To the contrary, the costs involved appear quite manageable in the context of a century or two of sustained growth.

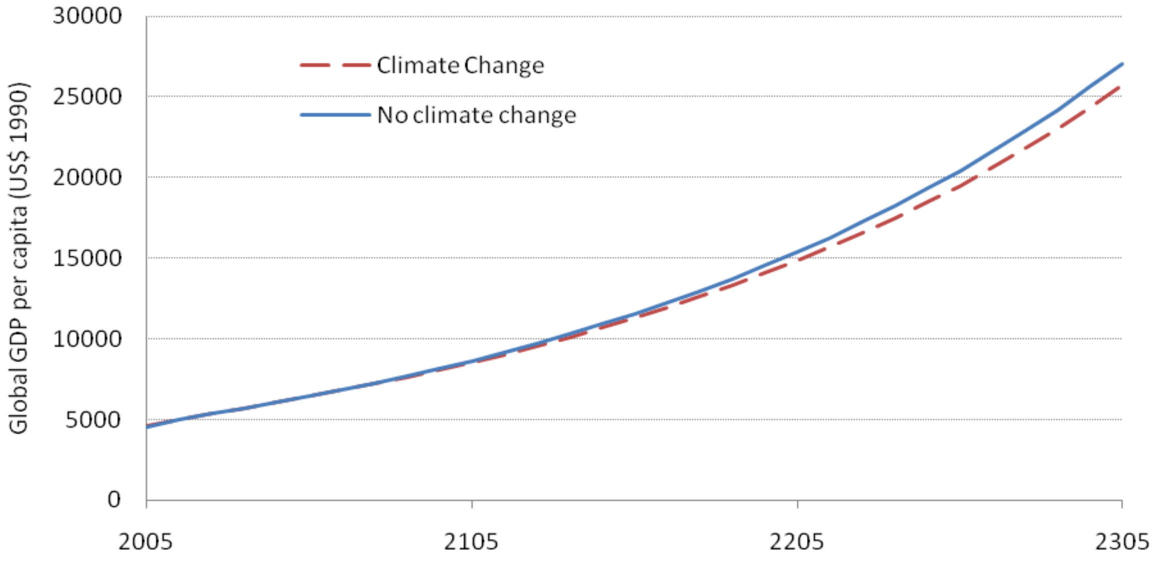

Figure 1. Damages from climate change in the Nordhaus and Boyer (2000) model up to 2305.

Notes 'No climate change' is a hypothetical world in which CO_2 emissions do not lead to global warming. 'Climate change' is a world with climate change but no mitigation.

Source: Nordhaus (2000).

Again, Nordhaus' low estimates of damages are typical of economic studies of climate change. The IPCC Fourth Assessment Report (2007a) survey of four economic models suggests that, for a 5 degree temperature increase, global output would take a hit of somewhere between 0 and 10 percent (IPCC 2007a, p. 822, Figure 20.3).

Low aggregate costs do not arise from a limited definition of damages. Nordhaus' damage function includes costs from non-market losses and the risk of catastrophic damage, in addition to market losses (Nordhaus and Boyer 2000, pp. 4.17-26). However, the quantification of these difficult-to-predict losses appears to be conservative. In the 2000 model, under no-mitigation, temperature rise reaches 4.5°C in 2285, causing a 5.1% loss to GDP (Nordhaus 2000). Such a rise lies at the top end of, or breaches, the probable range for activating the 'tipping points' of seven of the eight catastrophic global events, such as disruption of global weather systems and melting of major ice sheets, presented by Lenton *et al.* (2008, p. 1788) on the basis of expert opinion.[8] Breaching one of these tipping points, let alone several, must, one would imagine, have more impact on global welfare than implied by Figure 1.

Non-quantified analyses paint a more alarming picture of this scale of warming. A recent study by New *et al.* (2011, p. 6) find that a "..4 degrees Celsius warming could result in the collapse of systems or require transformational adaptation out of systems, as we understand them today." An earlier study by the Centre for International and Strategic Studies concluded that a 5°C increase "would pose almost inconceivable challenges as human society struggled to adapt.... The collapse and chaos associated with extreme climate change futures would destabilize virtually every aspect of modern life" (Campbell *et al.* 2007, pp. 7-9).

There are a number of reasons why conventional quantification might underestimate climate change damage. The models may not capture the fact that our willingness to pay for non-market damage will increase as our incomes rise and as the quality of environmental assets falls (Sterner and Person 2008). Modelling potentially catastrophic change is also inherently difficult. Traditionally, economic models have ignored the fact that any given increase in temperature will do increasing damage over time as the result of lagged feedbacks in the climate system. For example, a high temperature increase will eventually melt large amounts of ice and subsequently cause significant rises in sea levels. Yet economic models have typically assumed that the cost of climate change damage at a given point of time is unrelated to the extent of time for which any temperature increase has persisted.

Indeed, in his 2008 book, titled *A Question of Balance,* Nordhaus acknowledges the limitations of his approach to damage estimates. He concedes that "models such as the present one have limited utility in looking at the potential for catastrophic events….We

[8] These tipping points are: melting of the Arctic summer sea ice and the Greenland ice sheet (0-2°C); dieback of the Amazon (3–4°C); melting of the west Antarctic ice sheet, disruption of the Atlantic thermohaline circulation, disruption of the Sahara/Sahel and West African monsoon, and dieback of boreal forest (3–5°C); and disruption of the El Nino–Southern Oscillation (3–6°C).

cannot rule out the potential for catastrophic impacts that might justify trillions of dollars of abatement costs” (Nordhaus 2008, p. 147).

Nordhaus also acknowledges that the imposition of a temperature increase limit could be justified, even if it results in lower temperatures than emerge from cost-benefit analysis. This is precisely because there could be thresholds (or tipping-points) “at which the damage function turns up sharply and damages become infinite” (Nordhaus 2008, p. 72). In recognition that such thresholds might exist, Nordhaus has, at least since his 2000 work, allowed the possibility that it might make sense to impose various exogenous limits on admissible temperature increases or atmospheric concentrations.

While a constrained solution may be preferable to an unconstrained one (since it makes greater allowance for catastrophic risks), the limitation of this approach is that we are offered no guidance towards which of the different temperature increase bounds to accept. Nordhaus does provide benefit-cost ratios for the various constrained scenarios, so we can see the additional costs of tighter bounds.[9] But the reader is given no basis to decide whether the (external-to-the-model) benefits of imposing a tighter temperature increase bound justify these additional costs.

The support for moderate mitigation is also a function of assumptions made about projected emissions growth in the absence of mitigation. The lower emissions are assumed to grow even without mitigation, the less mitigation is required to achieve any given temperature target.

In Figure 2 the business as usual emissions projection of Nordhaus and Boyer (2000) are compared to scenarios from the widely-used Special Report on Emissions Scenarios (SRES) developed around the same time (IPCC 2000). Nordhaus’ 2000 projection is well below the median SRES projection, not to mention the rapid emissions growth of the A1FI scenario, the most pessimistic of the SRES scenarios. As Garnaut *et al*. (2008) and others (Pielke *et al.* 2008, Sheehan 2008) have showed, the SRES scenarios now appear to underestimate the

[9] See Nordhaus and Boyer (2000, p. 7.26) and Nordhaus (2008, p. 89).

course of emissions growth, particularly in Asia. In recent years, emissions have been at the top end of the SRES range (the A1FI scenario shown).

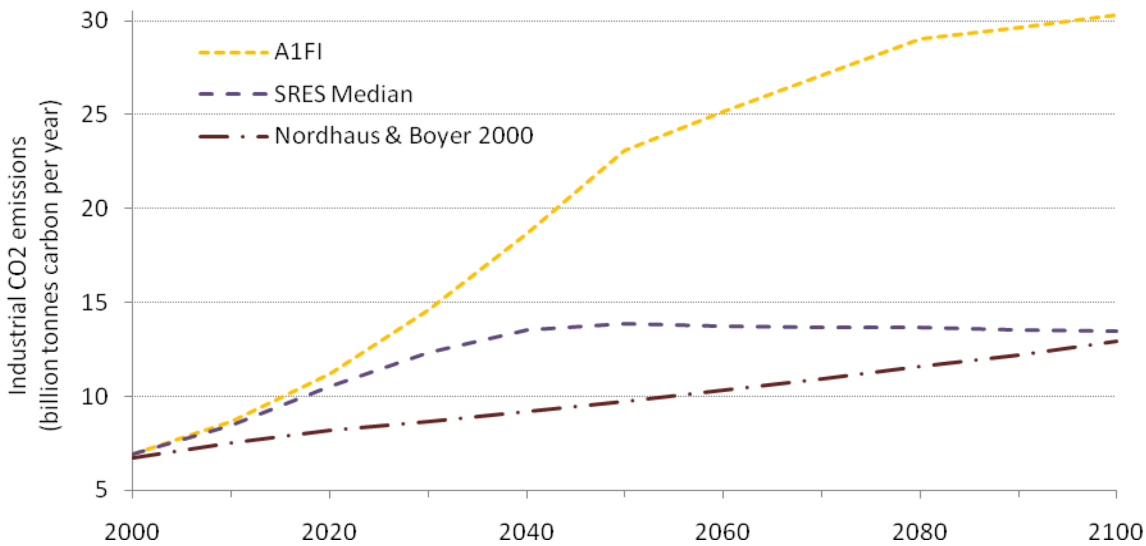

Figure 2. Nordhaus' projections of future emissions growth under business as usual compared to the median and the most pessimistic SRES scenario.

Notes: The SRES scenarios are 40 emissions projections combining various assumptions of future economic growth, emissions intensity of production, globalization, social attitudes to the environment and other variables. As the name suggests, the median SRES scenario is the median trajectory, which we calculate for the marker scenarios for each of the four main families. The A1FI (marker) scenario is the most pessimistic of the SRES scenarios in terms of emissions growth.

Sources: Nordhaus (2000), IPCC (2000).

3. The Stern Review

Although the Stern Review used the same cost-benefit framework as Nordhaus, Stern adopted a more eclectic approach drawing on different models and techniques rather than relying on a single IAM. Also, rather than search for the optimal degree of global mitigation, Stern calculated and compared the costs and benefits of only two scenarios: a no-mitigation and a mitigation scenario.

Climate change costs in the absence of mitigation were estimated in the Stern Review using Monte Carlo runs (multiple scenarios using different random combinations of key parameters) of a particular climate model (PAGE). The results of the different runs were then averaged and converted into a constant cost to consumption which, for a given discount rate, would give the same net present social welfare as is realized in the actual no-mitigation scenario (the so-called 'balanced growth equivalent'*)*. Different assumptions concerning non-market impacts, catastrophic outcomes, distributional impacts and the treatment of uncertainty gave a range of 5-20% of GDP in balanced growth equivalent terms for climate change costs under the no-mitigation scenario (Stern 2007, pp. 185-7).

Stern's mitigation scenario targeted 550 ppm, as a proxy for the range of 450-550 CO_2-e ppm[10] within which he argued "the stabilization goal must lie" (Stern 2007, p. 338). Although any level above 550 ppm was considered too risky, Stern argued that stabilization at 450 or below "is likely to be very difficult and costly" (Stern 2007, p. 338). Moreover, uncertainty prevents the establishment of "a narrow range" for concentration targets (Stern 2007, p. 339).

For the mitigation scenario, Stern used a simple marginal abatement cost approach to estimate that the costs of stabilizing emissions at 550 ppm would be between -1 and 3.5% of global GDP by 2050, with a most likely estimate of 1% (Stern 2007, pp. 258-65).[11] Stern assumed that mitigation costs would be fixed as a share of GDP every year, and that any residual costs from mitigated climate change be ignored. These simplifications gave Stern the famous comparison between the costs of action (1% of GDP) and the costs of inaction (5-20% of GDP), which he used to argue in favour of a 450-550 ppm target range, thus breaking with the pre-existing consensus.

Not only did Stern argue for a lower concentration and temperature target than had been advocated before, but he used this as the basis for arguing against the policy ramp. Stern argued for "strong action now" (Stern 2007, p. xv) because failure to act urgently would render a 550 ppm target unattainable, just as, in his judgement, significantly lower targets had already become.

[10] CO_2-e refers to carbon dioxide equivalent. This is a measure of the equivalent amount of carbon dioxide in the atmosphere required to give the same radiative forcing as all greenhouse gases. Stern and Garnaut typically refer to CO_2-e concentrations. Nordhaus refers to CO_2 only concentrations. Hence, 550 ppm in Nordhaus' work entails a higher concentration of all greenhouse gases than in Stern and Garnaut's work.

[11] The prospect of negative costs implies the possibility of economic gains from abatement alone, regardless of avoided damages.

Although his recommendations were radical, much of Stern's analysis was conducted within the bounds of mainstream opinion at the time. Stern assumed faster emissions growth in the absence of mitigation than Nordhaus, but still within the bounds of the family of SRES projections (see Figure 5 in the next section). Correspondingly, Stern's principal estimate for likely global warming without mitigation of approximately 3.4°C (above 1980-1999 levels) by 2100 (Stern 2007, p. 180), well within the 1.8 to 4°C range of best estimates in the Fourth Assessment Report (IPCC 2007b, p. 44).[12] Moreover, Stern's 1% of annual global GDP estimate for mitigation costs is close to the IPCC reported mean of 1.3% for a concentration target of 500-550 CO_2-e ppm (IPCC 2007c, p. 206).

Stern's estimates of the likely damage arising from climate change are if anything conservative compared to Nordhaus. Figure 3 directly compares Stern's most comprehensive estimates of likely damages for a range of temperature increases to those Nordhaus uses in his 2000 work. Stern's estimates are similar to Nordhaus' until about 2°C of warming, and significantly *lower* for higher temperatures.[13] This might seem surprising given Stern's call for urgent action. As we show below, it is not the damages themselves, but how they are accounted for that drives Stern's analysis.

[12] This temperature range covers the best (middle) estimates for warming arising from the six main SRES scenarios. The lower bound is from the B1 marker scenario and the upper bound is provided by the A1FI scenario. The other scenarios are A1T, B2, A1B and A2. See IPCC (2000) for further description.

[13] Note that negative damages for warming below 1°C in Nordhaus and Boyer (2000) implies that the net economic impact of climate change is positive on a global basis. This is a common feature of earlier work.

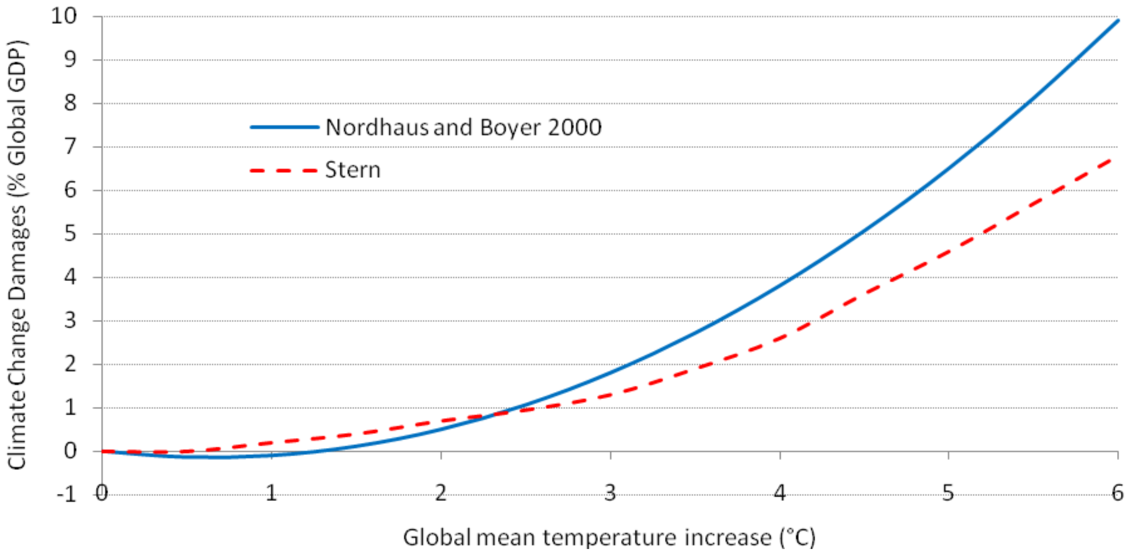

Figure 3. The damage functions of Nordhaus and Stern compared.

Note: The estimates for Stern's damages used here are drawn from the "High climate, market impacts + risk of catastrophe + non-market impacts" estimate displayed in Figure 6.6 (Stern 2007, p. 180).
Sources: Nordhaus (2000), Stern (2007).

In this regard, Stern made two important departures from conventional wisdom. One was to roughly double modelled aggregate damages to account for distributional concerns and uncertainty. Recall Stern's headline finding that climate change will cost 5-20% of GDP (using the balanced growth equivalent discussed above). The lowest bound (actually 5.9%) comes from measuring direct market impacts and the risk of catastrophe. Including non-market impacts increases this to 10.9%. But these modelled estimates of damages are then further adjusted.[14] First, an adjustment of about a quarter, to 13-14%, is needed, Stern argues, to reflect the fact that the poor will be disproportionately affected. Then a further adjustment up to 20% is needed to incorporate uncertainty. Stern concludes that the best estimate of damages lies between 13-14 and 20% (Stern 2007, pp. 185-7).[15]

[14] The summary of Stern's argument which follows is taken from Stern (2007), pp. 185-7.

[15] Stern cites Nordhaus and Boyer (2000) to support the view that taking account of the distribution of climate change damages would increase them by about one-quarter to 13-14%. For the second adjustment, Stern refers to an argument developed earlier in his report that under uncertainty, when we are unsure which probability distribution to use, we should take a weighted average of the best and worst expected utilities (Stern 2007, pp. 38-9). The best is 13-14% (as derived above), the worst, under more pessimistic assumptions about impact and also apply the adjustment for the distribution of impacts, is 20%. The final number would be a weighted average of 13-14% and 20%.

The second departure Stern made from the conventional wisdom concerned the discount rate for conversion of future costs and benefits into net present value equivalents. All economists agree that a dollar tomorrow is worth less than a dollar today, but by how much? Stern uses the standard formulation (known as the Ramsey equation) for determination of the discount rate, namely

$$r = \delta + \eta g$$

where

- δ (*delta*) is the pure rate of time preference: the rate at which we discount consumption in the future simply because it is the future – the more we do, the higher the discount rate
- η (*eta*) is a measure of inequality/risk aversion (formally known as the elasticity of the marginal utility of consumption): the rate at which we discount income because it accrues to people who are better off than us – again, the more we do, the higher the discount rate (assuming future populations are richer than us)
- g is the rate of growth in per capita income: the higher income growth, the richer people in the future will be, the higher the discount rate (assuming we are inequality averse).

Within this conventional framework, Stern argued for a much lower discount rate than earlier analysts had advocated (with the exception of Cline 1992). Nordhaus (2008), for example, argued that δ should be set to 1.5 and η to 2.[16] With per capita income growth of 2% up to 2050, the discount rate would be 5.5% for this period (Nordhaus 2008, p. 61). Nordhaus justified these parameter choices from market behaviour. That the resulting discount rate corresponded to after tax returns from various US capital markets is presented as evidence by Nordhaus that the parameter choices were correct (Nordhaus 2008, pp. 57-8).

[16] The following comparison between the authors refers to Nordhaus (2008) rather than Nordhaus and Boyer (2000) because the analytical framework used in the former study is closer to Stern's framework. Although the discount rates used in the two models are similar, the utility function used by Nordhaus changes between 2000 and 2008.

In contrast, Stern claimed that the parameters δ and η could not be accurately revealed from markets given the intergenerational context of climate change mitigation, and they must be assigned on a normative basis. He argued that that the only justification for setting the pure rate of time preference greater than zero was the risk of extinction and selected δ=0.1 as a small positive value, to represent the possibility of extinction. In Stern's view, any higher value represented arbitrary discrimination against future generations (Stern 2007, p. 54). Concerning η, the marginal elasticity of income, Stern argued for a value of 1 as representing a reasonable degree of concern for equity (Stern 2007, p. 55).

The discount rate arising from these parameter choices depends on the per capita income growth rate assumed. Table 1 uses two per capita income rates, 1.3%, the long-term (this century and beyond) rate used by both Stern and Nordhaus (Stern 2007, p. 184; Nordhaus 2008, p. 108) and 2%, the rate used by Nordhaus to 2050 (Nordhaus 2008, p. 61). With the higher growth rate, Stern's discount rate would be 2.1%, and Nordhaus' 5.5%. With the lower growth rate, the discount rates are 1.4% and 4.1%.

	Nordhaus		Stern	
δ	1.5		0.1	
η	2		1	
g	2	1.3	2	1.3
r	5.5	4.1	2.1	1.4

Table 1. Stern and Nordhaus discount rates and parameters.

Notes: See Ramsey equation in the text and accompanying notes for explanations of the different parameters.
Sources: Nordhaus (2008), Stern (2008).

A simple example shows the importance of the discount rate. Suppose that the cost of mitigation is, as Stern suggests, constant at 1% of GDP and that, in the absence of climate change, business as usual (BAU) per capita GDP growth of 1.3% would be observed, again consistent with Stern's analysis (p. 184). Assume also, consistent with Stern, that damages increase gradually to 2% by 2100 and then more sharply to 11.3% by 2200.[17] Post 2200, GDP

[17] These damages parameters are for the 'Baseline climate, market impacts + risk of catastrophe + non-market impacts' estimate for damages per unit temperature rise (see Stern 2007, Figure 6.6, p.180). In

grows at the same rate in both BAU and mitigation scenarios. Table 2 compares the net present value (NPV) of climate change mitigation under the preferred Stern and Nordhaus discount rate parameters from Table 1, as a percentage of no-mitigation GDP.[18]

NPV of mitigation vs. no-mitigation (relative to GDP)		
	'Stern'	'Nordhaus'
21st century	0.0%	-0.4%
22nd century	5.6%	3.8%
Post-22nd century	10.3%	10.3%
Total	2.6%	-0.1%

Table 2. The case for mitigation using Stern's and Nordhaus' discount rate parameters.

Notes: See the text for explanations and Table 1 for parameters. The costs of mitigation and no-mitigation are normalized by dividing by the GDP before damages or mitigation.

In Table 2, we can see that mitigation pays for itself over the first century with Stern discount rates, and that the benefits are substantial in the second, and thereafter. With a low discount rate, these distant benefits of mitigation matter a lot, and so overall mitigation has a positive net present value. Under Nordhaus-type discount rate parameters, mitigation is a net cost to bear in the 21st century. There are benefits in the following century, and beyond, but because these are heavily discounted they barely influence the aggregate valuation, and mitigation is not a worthwhile exercise.

Given the importance of the discounting assumption, it is not surprising that most critiques of the Stern Review focused on this issue. Some commentators argued that Stern was mistaken in taking a normative view to determining the discount rate. These critics claimed that the discount rate derived from the Ramsey equation had to be consistent with capital market returns, as it is capital markets that represent the opportunity costs of funds

Figure 6.5 (Stern 2007, p.178), Stern does not provide timeline values for this run. The 2200 value is deduced from the highest value for Figure 6.6. The 2100 value is inferred from the bounds provided by the other runs in Figure 6.5.

[18] For simplicity, zero population growth is assumed in this exercise. Note also that this analysis ignores that the discount rate is endogenous to the growth rate, which changes between the mitigation and no-mitigation scenario. A similar exercise was undertaken in terms of welfare, thereby avoiding any complications arising from an endogenous discount rate, and the results were very similar.

committed to mitigation that could otherwise be invested. Nordhaus (2007) and Tol *et al.* (2007) argued that Stern had selected an excessively low value for the pure rate of time preference (δ). Dasgupta (2007) made the case that Stern had set the measure of inequality/risk aversion (η) too low. This author argued that a value for this parameter of one was inconsistent with observed behaviour, as it implied savings well above observed levels.

We are ourselves sympathetic to Stern's normative approach. As noted by Deaton (2007, p. 4), "Whatever it is that is generating market behaviour, it is not the outcome of an infinitely lived and infinitely far-sighted representative agent whose market and moral behaviours are perfectly aligned, and who we can use as some sort of infallible guide to our own decisions and policies". However, it must be admitted that reliance on a low discount rate is, as a matter of practice, a tenuous basis for establishing an argument in favour of stringent mitigation, one which may not convince those which have a different view of the matter.

This analysis of the discount rate is incomplete because it takes no account of uncertainty, the appropriate treatment of which also dominated post-Stern reviews.[19] The parameter η measures risk as well as inequality aversion and so, under uncertainty, a high η might lead to high expected damages (since bad outcomes are given a higher weight), and so might support strong mitigation even if it also leads to a high discount rate (see Dietz *et al.* 2007, Smith 2011). Thus, once uncertainty is introduced, it is not as simple as saying that the higher the discount rate, the more moderate the optimal level of mitigation. The work of Dietz *et al.* (2007) suggests that this might not be the case for high values of η.[20]

The ramifications of uncertainty run deeper than this. A broader critique argues that cost-benefit analysis is not an appropriate framework for analysing climate change decisions precisely because of the high levels of uncertainty involved.

[19] For a comprehensive exploration of the Stern Review's methodology and associated critiques, see Barker (2008), Quiggin (2008) and others in the same issue of *Climatic Change* dedicated to the topic, as well as Cole (2008).

[20] In the work of (Dietz *et al*. 2007), damages fall as η increases to 2, but then grow as η increases further, though only for the high climate scenario, not the baseline-climate one.

The latter line of argument had been developed pre-Stern by Schneider (1997), Azer and Lindgren (2003), and Tol (2003), all of whom argued that the levels of uncertainty were (or could be) such as to make cost-benefit analysis an inadequate framework to guide decision making in relation to climate change. Post-Stern this argument was developed by Martin Weitzman in a series of papers (see Weitzman 2007a, 2007b, 2009). Weitzman argued that cost-benefit analysis was inappropriate for a problem which involved a small risk of catastrophic damage. Under certain so-called 'fat tail' conditions, Weitzman showed that such a risk could give rise to the expected utility of a no-mitigation scenario approaching negative infinity (see Weitzman 2009, pp. 6-9 for a formal illustration). For example, the IPCC Fourth Assessment Report's review of climate models showed a small probability (less than 3%) that without mitigation temperatures would rise by 6 degrees Celsius. Weitzman states that this would cause:

> ...a terra incognita biosphere…whose mass species extinctions, radical alterations of natural environments, and other extreme outdoor consequences of a different planet will have been triggered by a geologically instantaneous temperature change that is significantly larger than what separates us now from past ice ages (Weitzman 2007a, p. 717).

Whether or not it is useful to think about climate change as a 'fat tailed' problem (this has been challenged by Nordhaus 2009a and Pindyck 2010), the broader point about uncertainty is compelling one, and is increasingly recognized as such. As expressed by Yohe:

> ... pervasive uncertainty about the physical and economic consequences of climate change undermines the credibility of economically optimal policies that emerge from traditional benefit-cost calculations (2010, p. 212).

However, if cost-benefit analysis is not appropriate, it is not clear what is. Conceptualization of climate change as a 'risk management' problem has become popular (see Stern 2008, Ackerman *et al.* 2009, Kousky and Cooke 2009, Yohe 2010), but as Weitzman (2007, p. 723) himself notes: "we lack a commonly accepted usable economic framework for dealing with the sort of uncertainty which climate change involves."[21]

4. The Garnaut Review

The Garnaut Review had the advantage of coming after both the Stern Review and the academic furore that followed it. As a result, it was able to derive a methodology addressing the critiques of Stern outlined above. Although the scope of the Garnaut Review was to examine mitigation from Australia's perspective, rather than from the global viewpoint of Nordhaus and Stern, its methodology is applicable to either setting.

The Garnaut Review considered three international strategies and their ramifications for the Australian economy: a no-mitigation strategy, a 550 and a 450 CO_2-e ppm target. The 450 strategy was an overshooting one, in which concentrations exceeded the target and then approached 450 from above. It is roughly similar to what Stern would call a 550 ppm stabilization strategy (see the discussion in the next section), since Stern's scenarios do not allow for overshooting.[22]

Pairwise comparison of the no-mitigation to the 550 ppm strategy (Garnaut 2008, pp. 264-7), and the 550 to the 450 ppm strategy (Garnaut 2008, pp. 268-72) provided the basis for an ordering of strategies: 550 ppm was judged to be better than no-mitigation, but not as good as 450 ppm (Garnaut 2008, p. 268).

The Review distinguished between four types of climate change damages: directly modelled market costs such as reduced agricultural productivity; difficult to model market impacts such as infrastructure maintenance; costs from catastrophic climate change; and, non-market costs such as species extinction (see Garnaut 2008, pp. 253-62). Only the first two types were quantified.

[21] In response to this uncertainty, Weitzman himself suggested a policy of greater scientific and economic research into the likelihood and impact of worst-case scenarios, as well as assessing the cost-effectiveness of different options for dealing with catastrophic climate change from geoengineering (Weitzman 2009, p. 17).

[22] Note that in Garnaut's 450 'overshooting' scenario, concentrations actually reach slightly above 500 ppm before starting to decline. See Figure 4.4 in Garnaut 2008, p. 86.

The level of Australian mitigation, and subsequent costs, required for either global stabilisation target was determined on the basis of a proportional contribution to a global effort. The Garnaut Review defined Australia's effort in terms of the tradeable emissions entitlement it would be allocated under a variant of the contraction and convergence approach developed by the Global Commons Institute (2000). Within this structure, it was estimated Australia would be obliged to reduce emissions (strictly, emissions entitlements) by 2050 (from a base year of 2000) by 80 or 90 percent for a 550 or 450ppm target respectively (Garnaut 2008, p. 209).

For the first comparison between 550 ppm and no-mitigation, the costs of climate change were primarily assessed on a qualitative basis. As a result of projected rapid emissions growth without mitigation (discussed further below), the Garnaut Review predicted that without mitigation temperatures would rise over the course of the century by more than 5°C (Garnaut 2008, p. 92). The quantified costs of this would rise to above 7% of GNP by the end of the century. More importantly, it was argued that such a rapid temperature increase would bring about the 'terra incognita' highlighted by Weitzman and the 'chaos and catastrophe' discussed by the Centre for Strategic and International Studies (see the respective quotes in the previous two sections). The rapid emissions growth which Garnaut projected under business as usual transformed these catastrophic scenarios from low-probability risks for the next century to likely outcomes for this one. As the Review noted:

> To summarize, temperature increases ... associated with no mitigation .... would not lead to a marginal reduction in human welfare. Their impacts on human civilization and most ecosystems are likely to be catastrophic. (2008, p. 263).

Rather than struggling to quantify such large but uncertain costs, the Garnaut Review simply showed that the costs of mitigating climate change were, by contrast, moderate. Mitigation costs are relatively easy to quantify. From the gross costs of mitigation were subtracted the market-based (and therefore quantifiable) benefits of reduced climate change, giving the net costs of mitigation. The latter were estimated over the course of the century, and provided in net present value terms for two different discount rates: a low Stern-like rate of

1.4%, and a second higher, though still relatively low, rate of 2.7%.[23] In fact the choice of discount rate made little difference, and the two estimates were, in net present value terms, 3.2% and 3.3% of Gross National Product (calculated as the net present value of damages over the century divided by the net present value of GNP over the century; see Garnaut 2008, p. 270). The conclusion was that, regardless of the discount rate, moderate mitigation would come at a moderate cost and was preferable to likely catastrophe.

So moderate mitigation is preferred to none, but is stringent mitigation better still? To answer this question, the quantifiable costs of the two mitigation scenarios were compared. Again the notion of net mitigation costs was used: the gross costs of reducing emissions minus the benefit of a reduction in quantifiable climate change damages. The more stringent level of mitigation involved a significant increase in net mitigation costs. In net present value terms, the 450 ppm strategy cost 0.7 and 0.9 percent of discounted gross national product (GNP) more than the 550 ppm one (Garnaut 2008, p. 270), depending on whether the lower or higher discount rate was used.

Was the extra (almost) 1% of GDP associated with a 450 ppm scenario worth paying? Judged on the basis only of modelled results (net costs), it would not be. But the Garnaut Review argued it was, for two reasons.

The first was the insurance value of the more stringent strategy. The 550 ppm target involved a much higher probability of triggering climate 'tipping points'. For example, it was estimated that 550 ppm would involve a 26 percent chance of initiating large-scale melting of the Greenland ice sheet, whilst 450 ppm entailed a 10 percent probability (Garnaut 2008, p. 272). While such numbers can only be illustrative, they were used by the Review to argue that the insurance value of reducing such risks in adopting a 450 ppm target is worth 1 percent of GNP.

[23] See Garnaut (2008, pp. 18-21) for a discussion of these alternative discount rates. The Garnaut Review followed Stern's approach to the pure rate of time preference, using a near zero value of 0.05. For the lower rate η=1 and for the higher η=2.

Second, this insurance value was augmented by a reduction in likely non-market damages (which, like catastrophic damages, were not included in the quantification of net costs), such as a lower likelihood of the destruction of the Great Barrier Reef (Garnaut 2008, p. 272).

The Review's judgement was that the more stringent mitigation, though more expensive, was worth it. On this basis, the Garnaut Review supported a 450 ppm target. It did, however, like the Stern Review, cast doubt on its feasibility. It argued that an "initial agreement on a global emissions path towards stabilization of the concentration of greenhouse gases at 550 CO_2-e is feasible" (Garnaut, 2008, p. xxxviii), and that "450 CO_2-e is a desirable next step" (*ibid*). It would thus be fair to characterize Garnaut as arguing for a 450-550 ppm target range, with a preference that the world should end up at the bottom of that range.

The Garnaut Review is solidly in the tradition of cost-benefit analysis (see Chapter 2 of the Review for an exposition). Yet it is a very different sort of cost-benefit to that conducted by Nordhaus or Stern. It relies heavily on qualitative analysis. Some quantification of benefits is undertaken, but on this basis alone, no mitigation would be preferred to moderate mitigation, and moderate to strict. That the Review's final ordering is the opposite of this underlines the importance of the qualitative analysis.

In some regards, the comparative analysis of the stringent and moderate mitigation strategies could be viewed as occurring within a risk-management framework. Certainly, arguments about avoiding catastrophe are important to the Garnaut conclusions. Yet, as noted earlier, it is not clear just what a risk-management approach is. Often the analogy of insurance is invoked (Weitzman 2009, Ackerman *et al.* 2009). Yet choices about insurance themselves hang on comparisons of costs (of the premium) with benefits (if it is invoked). Moreover, the insurance analogy can be misleading. One usually takes out insurance against low-probability events. The catastrophes associated with a no-mitigation scenario are not low-probability outcomes but likely outcomes, as the Review stresses.[24] For these reasons, we view the Garnaut analysis in the tradition of qualitative cost-benefit analysis (as argued for by van den Bergh 2004) rather than risk management.

If one of the striking features of the Garnaut analysis is its reliance on qualitative analysis, another is the insensitivity of results to the use of discount rate. The quantified net costs of climate change mitigation are positive (or the benefits negative) over the course of the century. Hence the specific discount rate chosen has little impact on the quantitative part of the analysis. Implicitly, the higher the discount rate, the lower the benefits of avoiding climate change the next century, but there is no attempt to quantify these benefits. In the case of no-mitigation, the implicit argument is that the costs of climate change are so large that it will be worth avoiding them at moderate cost for any reasonable range of discount rates. And for the case of 450 v 550 ppm, the implicit argument is that the avoidance of risks this century and next associated with a 450 ppm strategy is worth paying 1% of GNP for over the course of the century (in net present value terms), again for any reasonable range of discount rates.[25]

Garnaut echoed Stern's call for urgent action, not only because he supported an even more ambitious target, but because he also assumed higher underlying growth in emissions. The Garnaut Review regarded the rapid growth in emissions during the first part of the 21st century not as an anomaly, but as an indication of future trends. Garnaut argued that existing projections, bounded largely by the SRES scenarios framing Stern and Nordhaus' analysis, did not fully account for: accelerating growth in developing countries; the halt of declining energy intensity of growth in the Chinese economy; and the rising carbon intensity of global energy production, particularly due to greater coal consumption (Garnaut 2008, pp. 55-8).

[24] One implication of this is that the modelled costs of mitigation in the Review exclude the costs of catastrophe, even if the catastrophe is likely. Not modelling catastrophic costs is not because they are low probability but because they are simply too difficult to model.

[25] If one uses a much higher discount rate (say 5.5%) then the "450 premium" becomes 1.1%. Thus the 450 scenario does become relatively more expensive as the discount rate increases. However, the increase makes little difference, and it would not influence judgements of the sort the Garnaut Review calls on us to make, and indeed makes itself.

Figure 4 compares industrial CO_2 business as usual emissions from Stern, Nordhaus, and Garnaut. Stern assumed significantly higher future emissions than Nordhaus, and Garnaut significantly higher than Stern. Indeed, Garnaut's projections are comparable with those of the most pessimistic of the SRES scenarios, A1FI.

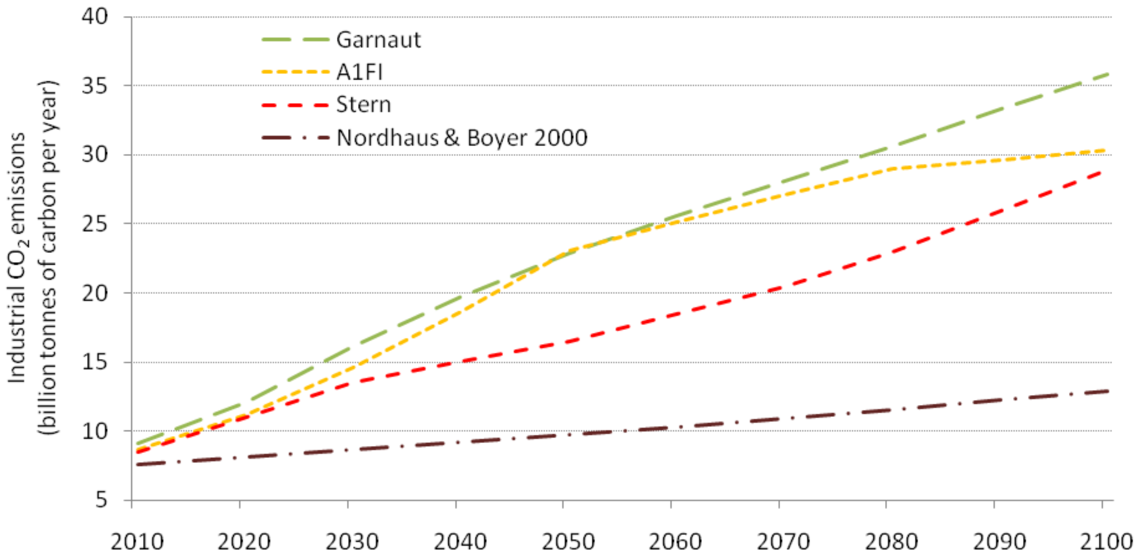

Figure 4. Garnaut, Stern and Nordhaus business as usual industrial CO_2 emissions growth.
Note: Stern uses A1 of the SRES scenarios for his business as usual projections.
Sources: Garnaut (2008), SRES (2000), Nordhaus (2000)

5. Converging views

As noted in the introduction, the views of the authors which this paper examines have not stayed static. This section gives the most recent views of Nordhaus and Stern, and compares them with those of the Garnaut Review.

Nordhaus has not changed his basic approach, which continues to rely on model-based cost-benefit analysis, but his results have shifted dramatically. Comparing recommended deviations from business as usual in Nordhaus and Boyer (2000), Nordhaus (2008), and Nordhaus (2010), as Figure 5 does, shows just how much Nordhaus has shifted away from the extremely gradual response he once advocated.

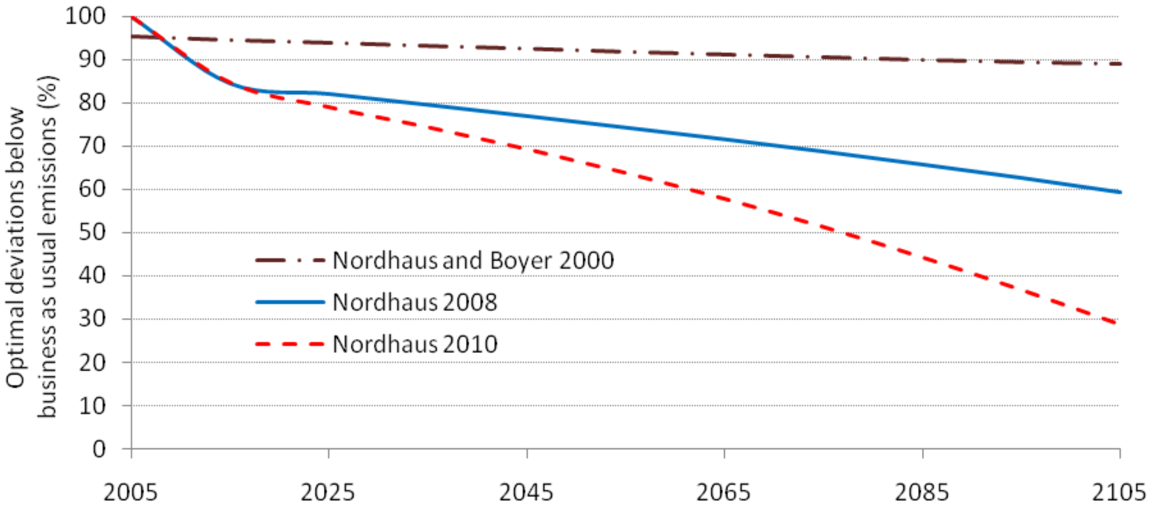

Figure 5. Optimal deviations below business as usual for different Nordhaus models 2000-2010.

Notes: As mentioned previously, Nordhaus uses two versions of a similar model in his analyses: DICE and RICE. They are calibrated to give similar results. The only areas with major discrepancies for the 2000 model are the control rate (essentially, the inverse of deviations below business as usual) and the optimal carbon price. Hence, we use the results from the primary model for the 2000 study, RICE, in this graph and also Figure 7.

Sources: Nordhaus (2000, 2009b, 2010b).

Whereas annual industrial emissions peaked in 2225 and 2115 for the 2000 and 2008 models respectively, Nordhaus' most recent study describes an optimal emissions trajectory with a maximum in 2045 (Nordhaus 2000, 2009b, 2010b). Figure 6 illustrates.

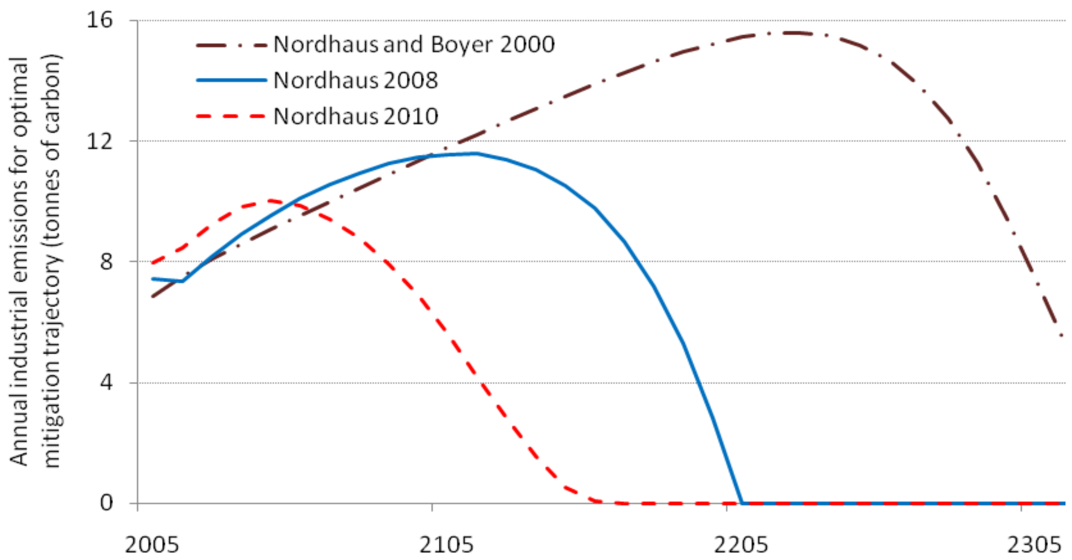

Figure 6. Optimal emissions trajectories for different Nordhaus models 2000-2010.

Sources: Nordhaus (2000, 2009b, 2010b).

More mitigation requires a higher carbon price. Nordhaus regards carbon prices as "[p]erhaps the most important outputs" of his modelling (Nordhaus 2010). Figure 7 shows how Nordhaus' view of the optimal carbon price has changed over time.

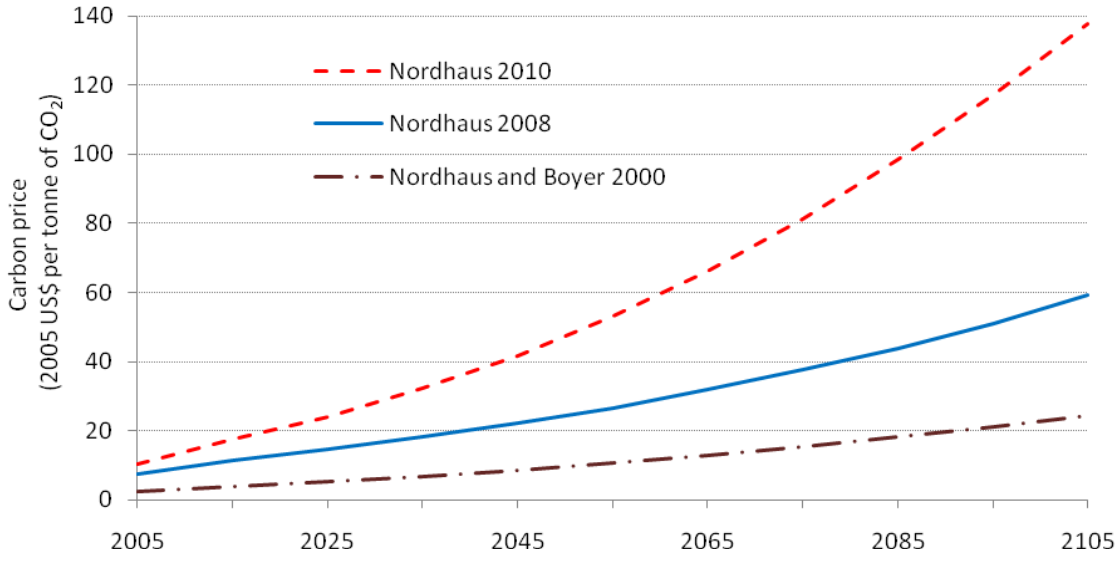

Figure 7. Optimal carbon price for different Nordhaus models 2000-2010
Notes: See notes to Figure 5.
Source: Nordhaus (2000, 2009b, 2010b)

There are several factors driving these substantial shifts towards greater ambition. First, the temperature target at which Nordhaus now thinks we should aim has fallen considerably, as Figure 8 shows. In 2000, Nordhaus thinks we should tolerate a temperature increase of up to 4.4°C; by 2008 this has fallen to 3.5°C, and by 2010 to 3.0°C.

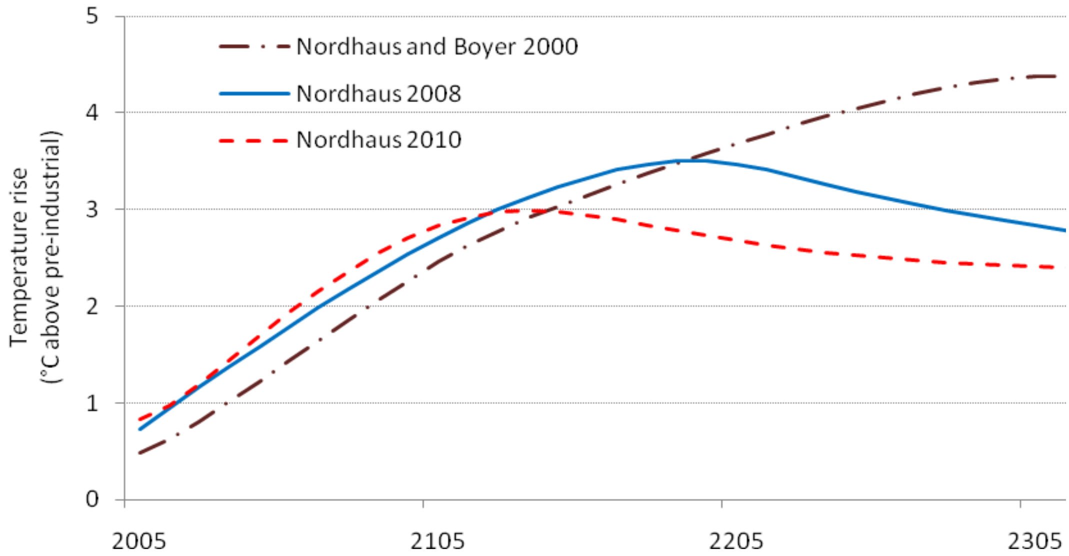

Figure 8. Global warming associated with optimal mitigation for different Nordhaus models 2000-2010.
Source: Nordhaus (2000, 2009b, 2010b)

Temperature targets in turn have fallen for a variety of reasons. As Figure 9 shows, the damages attached to climate change are revised upwards in 2008 at lower temperature levels and then again in 2010 for high temperatures.. In earlier discussion of Nordhaus' modelling, we pointed out that his representation of damages did not allow for any significant lagged response to high temperatures within the climate system. The addition of separate damages from sea-level rise to the damage function addresses this precise issue in the 2010 model. Where there is no mitigation, as Figure 9 shows, damages continue to rise even once temperatures have stabilized at just under 6°C during the 24th century.[26] In order to avoid extremely large damages in the vicinity of 30% of Global GDP, it is optimal to tolerate only a lower temperature increase, even though the prospect of disaster lies so far in the future.

[26] Nordhaus assumes in his 2008 and 2010 models that, even under business as usual, there exists a "backstop technology" (or zero-carbon emissions technology) that is adopted several centuries in the future. Therefore, emissions, and hence temperature rise, are assumed to cease at some point, even without mitigation.

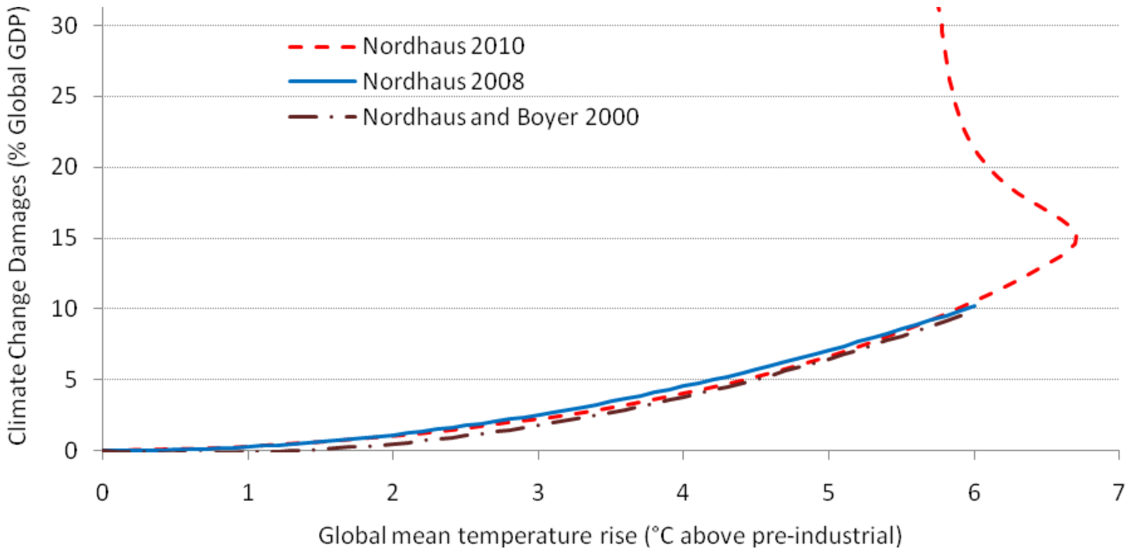

Figure 9. Damage functions for different Nordhaus models 2000-2010.

Notes: The Nordhaus (2010) 'damage function' traces out how temperatures and damages rise over time under business as usual, with, after a certain point of time, increasing damages for a given level of temperature increase due to damage from sea-level rise.

Source: Nordhaus (2000, 2009b, 2010b)

Other factors contribute to the fall in the temperature target. Between 2008 and 2010, Nordhaus revises downwards his discount rate, on account of the inequality/risk aversion parameter, η, falling from 2 to 1.5 (Nordhaus 2010b). He has also revised upward over time his temperature sensitivity parameter in line with changes in scientific thinking, so that a doubling of atmospheric carbon dioxide concentration which was assumed to lead eventually to 2.9°C of warming in 2000 was assumed instead to lead to 3°C of warming in 2008 and 3.2°C in 2010.

Another important change in Nordhaus' work over time is an upward revision in business as usual emissions, as Figure 10 illustrates. As mentioned earlier, there is a massive increase in projected emissions (without mitigation) between the 2000 and 2008 models, and a further more moderate increase (though only over the course of this century, not the next) between 2008 and 2010.

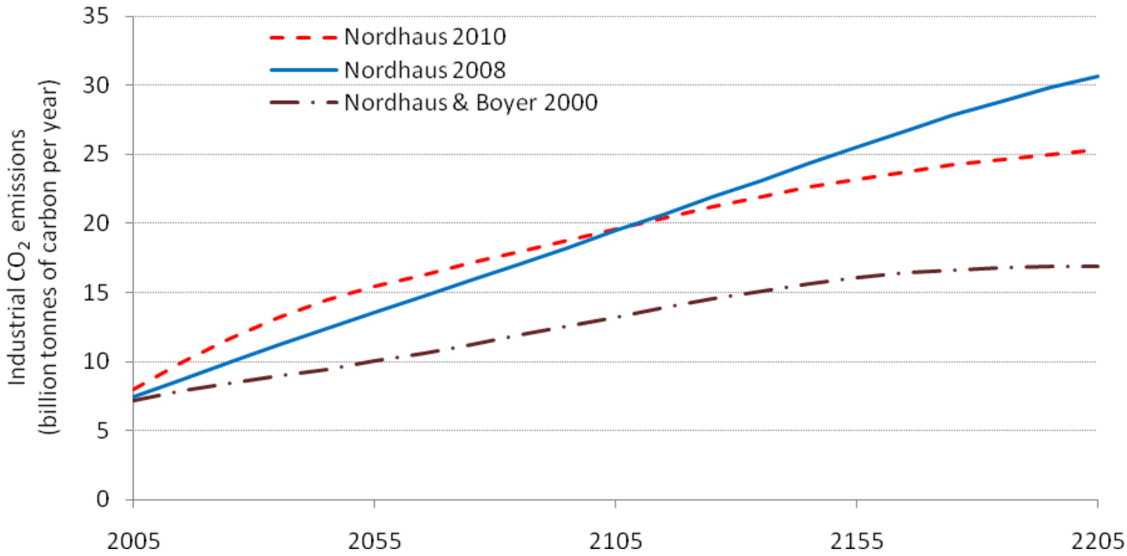

Figure 10. Business as usual industrial CO_2 emissions for different Nordhaus models 2000-2010.
Source: Nordhaus (2000, 2009b, 2010b).

The large change between 2000 and 2008 is driven by two factors. Firstly, Nordhaus' 2008 model assumes that, gross of climate change damages and abatement costs, we will be much wealthier in the future. By the start of the 22nd century global per capita income is US$ 33,242, as compared to US$ 13,066 in the 2000 model (both 2005 US dollars) (Nordhaus 2000, 2009b).[27] Secondly, the author assumes that the global rate of 'decarbonization' (or the fall in the proportion of CO_2 emissions produced per unit of GDP) is much lower, largely reflecting the surge in emissions from China (Nordhaus 2008, p. 48).

To summarize, a lower ultimate temperature target, and higher business as usual emissions both lead to the conclusion that more mitigation is needed, and earlier. As Figures 5-7 show, Nordhaus' work can no longer be taken to support the earlier consensus view of economists that "modest controls are generally optimal."

Stern's thinking has also evolved. He has increased the value attached to the marginal elasticity of consumption from 1 to 2 (Stern 2008, p. 15), increasing his discount rate to 2.7% for a per capita income growth of 1.3%. However, if anything, he thinks the case for urgent action is even stronger now, since his earlier work underestimated: emissions growth,

[27] This doubling of projected income growth becomes a four-fold disparity 100 years later (Nordhaus 2000, 2009b).

weakening of the carbon cycle, climate sensitivity, and damages for a given temperature increase (Stern 2008, p. 28). He therefore now argues that 550 CO_2-e ppm is "much too risky" as an upper limit and 500 ppm is a more acceptable ceiling (Stern 2009, p. 39). Most fundamentally of all, Stern now downplays the importance of cost-benefit approaches to climate change, arguing that it should be approached as a "risk management" problem (Stern 2008, p. 7), and that a "bottom-up, disaggregated, less formal risk evaluation approach is preferable to aggregate modelling in investigating the case for action" (Stern 2008, p. 23).

Table 3 attempts to set out this emerging consensus, both its extent and its limits. We see first a convergence in discount rates (compare the much broader range in Table 1).

Second, we see very similar temperature rise target ranges. We state Nordhaus' target range '3°C or below.' In Nordhaus (2010), Nordhaus gives a 2°C constraint considerable prominence. He uses it as an exogenously imposed constraint, and finds that satisfying this constraint has a net present value relative to no mitigation. We present Stern's target temperature range as 2-2.4°C. Stern does not present a temperature range target, but a 2-2.4°C increase is the range presented by the IPCC in its Fourth Assessment Report (IPCC 2007c, Table SPM.5) as associated with the CO_2-e stabilization target range of 445-490 ppm, which broadly corresponds to Stern's target range. Garnaut's target is the most ambitious of all, at 2°C.

Third, we present their optimal stabilization target range. Here, note that only Stern restricts himself to what are strictly speaking stabilization scenarios. Nordhaus and Garnaut both allow overshooting. But again, the comparability is clear.

The fourth row shows how demanding the target range is for each author. For this, to abstract from differences in target ranges, we here compare: Nordhaus' 2°C scenario, Garnaut's 450 ppm (overshooting) scenario, and Stern's 500 ppm (stabilization) scenario. There is little difference in what is required by 2020. All three authors demand a reduction in emissions below business as usual by 20-25%. But after that, positions start to diverge. Recall that Garnaut assumes higher business as usual emissions growth than Stern (see

Figure 5), who is well above Nordhaus.[28] As a result, Garnaut demands the highest cuts to achieve the same target, Nordhaus the lowest and Stern is in between. The differences are significant, though not overwhelming. By 2050, Garnaut requires an 82% cut below business as usual, Stern 75%, and Nordhaus 62%.

The final row shows the global carbon price computed to achieve the amount of mitigation required. Stern does not provide these results, but Garnaut and Nordhaus do (Garnaut provides a range: see Figure 11.1 of Garnaut 2008). The Nordhaus price is lower, but the gap falls over time in relative terms.

		Nordhaus	Stern	Garnaut
Discount rate (for g=1.3)		3.5	2.7	1.4-2.7
Temperature rise target range (above pre-industrial)		3°C or below	2-2.4°C	2°C
Stabilization level target range		500 ppm or below (CO_2 only)	450-500 ppm (CO_2-e)	450 ppm (CO_2-e)
Deviation from BAU (point estimates for reductions in annual emissions to meet a 2°C target)	2020	25%	24%	20%
	2025	29%	40%	39%
	2030	35%	49%	56%
	2050	62%	75%	82%
Carbon price (to meet a 2°C target)	2020	$30		$41-46
	2050	$120		$110-154

Table 3. Comparison of the contemporary Nordhaus, Stern and Garnaut positions.
Notes: The optimal path in Nordhaus (2010a) peaks at just under 600 CO_2 ppm, before stabilizing at around 500 ppm. Nordhaus' model runs are based on decadal intervals starting at 2005. The figures for deviation for BAU in 2020, 2030 and 2050 for this author are obtained by linear approximation between intervals from data in Nordhaus (2010b) for all CO_2 (including from land-use change and forestry). The trajectory used for the Stern 2°C target is the 500 ppm overshoot emissions path that stabilizes at 450 ppm (2007, Figure 8.4, p. 223). Carbon prices are with respect to tonnes of CO_2 and are in 2005 US$, using an exchange rate of $A1=$US0.77.
Sources: Nordhaus (2010a, 2010b, 2009b), Stern (2008), Garnaut (2008).

[28] Stern has recently emphasised that emissions growth in the Stern Review were probably underestimated, thus increasing the urgency of action (Stern 2008, p. 22).

6. Conclusion

The first decade of the twenty-first century was a period of flux for the economic analysis of climate change. Out of the debate and discussion has emerged a multiplicity of methodologies and a shift in conclusions. Our three prominent authors illustrate both these points. Nordhaus still uses quantitative model-based cost-benefit analysis. Garnaut uses a much more qualitative cost-benefit analysis. And Stern has moved away from cost-benefit analysis altogether towards a risk-management approach.

This methodological pluralism is, to our mind, a good thing. We are attracted to the simplicity of the Garnaut Review (on which some of us worked). As we argued earlier, we think a more qualitative approach to cost-benefit analysis has advantages over both a more quantitative cost-benefit analysis (which suffers from artificial precision) and a risk-management approach (which lacks conceptual clarity). However, the complexity of climate change suggests that a variety of approaches can be defended and should be used. There is certainly more to debate methodologically than what the discount rate should be. This is one area where differences have narrowed (see Table 3), and, as Smith (2011) argues, the earlier strong association between choice of discount rate and stringency of mitigation target is now weaker.

Not only have methodologies broadened over the last decade, but conclusions have changed, leading to a situation at first of divergence (from the old consensus) and then convergence (to a new consensus). For a range of reasons, Nordhaus has come to favour much more urgent action and ambitious targets. Stern and Garnaut have adjusted some of Nordhaus' parameters and/or used somewhat different methods to arrive at the conclusion that still more urgent action and even more ambitious targets are needed.

The first main point of the new consensus on substance among the three economists studied in this paper is that we should limit average global temperature increases to 3 degrees Celsius above pre-industrial levels or below.[29] There might still be disagreement

[29] At the end of her survey of the same three authors, Smith concludes that "each of Stern, Garnaut and Nordhaus find that immediate action consistent with meeting the international community's two degree

about how far below three degrees temperature increases should be capped: Garnaut and Stern think that restricting temperature increases to below 3 degrees would be better than allowing them to reach three. Nordhaus seems willing to contemplate that a 2 degree outcome might be better than a 3 degree one, but does not give a definitive view on this.

The extent of this particular divergence of views should not be overstated. All three authors express serious reservations about the difficulties of restricting temperature increases to two degrees (see the earlier references in relation to Stern and Garnaut, and Nordhaus (2010, p. 11724)). If all three share the opinion that 3 degrees is either optimal or too high, *and* they all agree that keeping increases much below 3 will be extremely difficult, then there is not much of a range left to further narrow.

Nordhaus, Garnaut and Stern also all now agree that substantial deviation from business as usual is required, and soon. For example, they agree that to hit a 2-degree target will require a reduction from business as usual by about 20% by 2020 and by 60-80% by 2050. None of them conform to the earlier consensus that "modest controls are generally optimal" (Kelly and Kollstad, 1999). To the contrary, the policy ramp is by now pretty steep for all three, even Nordhaus, as Figure 7 shows.

Looking at these two areas separately – temperature target ranges, and the emissions reductions required to achieve them – does admittedly exaggerate the conformity of views between the three authors. Nordhaus' optimal policy (which limits temperature increases only to 3 degrees) requires only a 30% reduction below business as usual by 2050, well below the 60% required for his 2-degree target. Thus, although there is more agreement than before, there is by no means a complete consensus. This is also evident from the carbon prices they propose. Nordhaus' prices are lower in early years even for the same temperature target as Garnaut, partly because he requires less mitigation and probably because he assumes lower marginal mitigation costs.

temperature goal is worthwhile."(2011, p.22) With respect to Nordhaus, this is based on his conclusion, noted earlier, that constraining temperatures to rise by no more than 2 degrees has a positive net present value relative to no mitigation. We concur that this is another point of agreement, and one which our more general formulation tries to capture.

There are at least two main areas which could lead to a further "closing of the gap". First, it seems clear to us that Nordhaus is underestimating emissions growth under business as usual. The SRES scenarios are simply no longer credible, but Nordhaus' business as usual projections continue to largely track the middle of the SRES range. An upwards adjustment in BAU emissions projections would, of course, increase the costs of mitigation, but also would most likely, we speculate, further increase the extent of adjustment Nordhaus would view as needed.

Second, more explicit treatment of the value of avoided catastrophic risk is needed, again on the part of Nordhaus. His approach identifies the costs of a temperature-constrained scenario, but not the benefits (since these are, by definition, outside the model, and only modelled benefits are presented). More explicit (though not necessarily modelled) consideration of the benefits of avoiding risky temperature increases would presumably provide some justification for aiming for a lower temperature increase than that specified by the optimal trajectory emerging from the model.

Not only are there differences between our three authors, but, of course, not all economists support the more demanding position now taken by them. Tol (2009b, p. 27) argues that the optimal mitigation policy would allow atmospheric CO_2 concentrations to rise beyond 800 ppm. He justifies this on the basis of cost-benefit analysis, even though Tol himself once showed that the uncertainties of climate change may render cost-benefit analysis useless as a decision framework (Tol 2003). Mendelsohn (2009) rehearses the traditional arguments in favour of modest and delayed mitigation.[30] However, he underestimates the speed with which catastrophic events may approach (given rapid emissions growth), and places a high level of faith in risky geoengineering solutions as an alternative to stringent mitigation. Perhaps geoengineering will be part of the climate change solution. But, as many authors have noted, all one can justify at this stage is more research (see for example Schneider 2008). Yohe *et al.* (2008, p. 37) also support moderate mitigation but the authors undermine their case by themselves acknowledging that their policies do not "reduce significantly the risk of some profound impacts across all sectors and in all regions."

[30] For example, he asserts that climate change damages will amount to between 0.1 and 0.5 of global GDP in 2100 (Mendelsohn 2009, p.13).

Though disagreements remain, there has nevertheless been a sea-change in economic thinking in this area. Prior to the Stern Review, the consensus among economists was that even 3 degrees or 550 CO_2-e ppm target was too ambitious a target (Tol and Yohe 2008, p. 240), and that, as cited earlier, “modest controls are generally optimal.” There is not yet a new consensus. But the old consensus has been overturned not only by relative newcomers to climate change such as Stern and Garnaut but by the more recent results of the most established climate change modeller, Nordhaus. This has not been adequately appreciated. Other authors continue to contrast Stern’s call for urgent action with Nordhaus’ counsel in favour of a slow start: see, for example Mendelsohn (2009) and Smith (2011). Nordhaus himself (2008, 2010) continues to emphasize how his conclusions differ from those which would hold if Stern’s discount rate parameters were applied within his model. This is no doubt the case, but it is equally, and more importantly, the case that Stern’s conclusions using his method are not that much different from Nordhaus’ using his.

Unfortunately, the strongest contrast is not between new and old views on climate change, but between the trajectory the world should be on, and the one on which, sadly, it is still stuck.[31] That the case for action on climate change has evolved more than action itself should give us all deep pause for thought. The world is likely on a collision course with catastrophe. As Garnaut (2008, p. 263) puts it:

> To point to the devastating impact of temperature increase for this century....is not to be alarmist. It is simply to recognise the reality of rapid emissions growth...”

Eventually, it is likely that as temperatures continue to increase, the world will be forced to take substantial action. How much of a price we end up paying for delay remains to be seen.

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[31] Global action on climate change mitigation has increased over recent years, and there has been some progress in reaching a global agreement. It is hard to be confident yet though that we have, as a world, deviated significantly from business as usual.

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