Discounting, risk and uncertainty in economic appraisals of climate change policy: comparing Nordhaus, Garnaut and Stern

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Abstract

The Stern (2006) and Garnaut (2008) Reviews argued for strong and early action to mitigate greenhouse gas emissions, while Nordhaus (2001, 2006, 2008a, 2010a) has consistently argued for weaker and more gradual policy action. While the economic debate immediately following the Stern Review focused on discount rates, the more recent literature draws attention to a wider range of issues that underlie these different policy prescriptions. This paper has two aims. The first is to place the Garnaut Review's approach to discounting in the context of the literature on discounting in climate change policy, including recent applications of theories for intertemporal choice that deal explicitly with non-marginal outcomes while being robust to the use of higher discount rates. The second is to shed further light on claims about the relative importance of discounting and risk by examining their treatment across as well as within models used for climate policy evaluation. We reconcile differing analyses of the relative importance of risk and discounting by reiterating the significant differences in the treatment of risk and uncertainty across models. While discounting is important, several pieces of recent research highlight the importance of two key relationships – between greenhouse gas concentrations and temperatures, and between temperatures and the economic impacts of climate change – in determining the projected outcomes of unmitigated climate change and hence optimal mitigation policy. Nordhaus's central choices for these relationships, combined with a minimal approach to uncertainty, are instrumental in DICE's projections of the relatively modest outcomes of unmitigated climate change, and hence its prescription that the optimal amount of mitigation is also modest. In contrast, world leaders have agreed that deep emissions cuts are required. We outline the emissions trajectories and risks associated with Nordhaus's preferred climate policy and paths consistent with meeting the international community's two degree temperature goal. While Garnaut and Nordhaus both use deterministic models to evaluate climate policy, Garnaut endorses global action to stabilise concentrations of greenhouse gases at 450ppm CO_2-e or lower – in line with the two degree temperature goal – as being consistent with Australia's national interest. Considering Garnaut's 'off-model' treatment of risk and uncertainty and comparing it with Stern's formal analysis, we find that both quantitative and qualitative approaches to incorporating uncertainty and risk can be appropriate.

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1. Introduction

Leading public policy economists Lord Stern and Professor Garnaut conducted major reviews of climate change policy for the United Kingdom and Australian governments in 2006 and 2008.[2] The overarching policy questions addressed by each Review were whether mitigation of greenhouse gases was desirable and, if so, to what extent.[3] While carefully stressing the limits of quantitative analysis, both Reviews judged that comparing the costs and benefits of mitigation would provide useful information for policymakers (Stern 2007:163, 188; Garnaut 2008:247-250). The main costs of mitigation (investment in emissions reductions) are expected to stabilise this century, while the benefits (avoided adverse impacts from climate change) accelerate this century but accrue mainly in the next century and beyond (Garnaut 2008:249). As such, the treatment of current versus future wellbeing is central to any analysis of policy options. After the Stern Review was released in late 2006, there was a lively discussion among economists[4] about the Review's approach to future wellbeing and the importance of its approach to discounting in driving differences between the Review's prescription of strong and early mitigation action and that of many earlier studies. In particular, William Nordhaus (2006), a pioneer of cost-benefit analysis of climate change policy, argued that Stern's approach to discounting drove an incorrect policy prescription and that mitigation action should be moderate and gradual. While not always appreciated by Australian commentators, as the Garnaut Review final report appeared nearly two years after Stern's, Garnaut was able to consider that recent discussion on approaches to discounting in climate change policy when developing his Review's approach.

This paper discusses the approaches to discounting and risk in evaluations of climate change policy. It proceeds as follows. The next section discusses approaches to discounting, distinguishing between the appropriate approach for marginal and non-marginal policy problems and normative and positive approaches to discounting. We summarise each of Stern's, Garnaut's and Nordhaus's approaches and briefly discuss a recent application of an alternative approach to intertemporal choice that could complement current approaches to discounting in climate policy evaluation. Section three turns to the relative importance of different approaches to discounting and risk in driving differences between economists' policy prescriptions. Outlining the approaches adopted by Stern, Nordhaus and Garnaut, we note that while discounting is important, it is not the sole driver of mitigation policy prescriptions. Recent research shows that Nordhaus's approach to uncertainty, coupled with choices for two key relationships, are influential in his projections of the modest disutility of unmitigated climate change and hence his 2008 finding that it is optimal to engage in only modest mitigation. We compare the risks associated with his preferred policies with the risks associated with paths consistent with the international community's goal of limiting temperature increases to two degrees Celsius on pre-industrial levels and discuss Garnaut's decision to analyse risk and uncertainty outside of his

[2] In this paper, references to the Stern Review are to the 2007 published version.

[3] Stern's (2007:ix) Terms of Reference instructed him to conduct a broad global analysis and draw specific lessons for the UK; Garnaut's (2008:xvi) required him to determine the medium- and long-term climate policy options that are in Australia's national interest.

[4] See for example Dasgupta (2007), Beckerman and Hepburn (2007), De Long (2006), Quiggin (2006), Dietz et al (2007a, b); Weitzman (2007) and Stern (2008).

Review's formal modelling framework. Section four concludes with implications for economists contributing to the public debate on climate change.

2. Approaches to discounting

Exogenous versus endogenous discounting

The criticism that "the" discount rate is wrong in any of Stern, Garnaut or Nordhaus' work reveals a basic misconception about the approach to discounting (Stern 2008: 12). While the approach of each differs, none of these three economists uses a single discount rate. Rather, the real discount rate depends on the rate of growth of per capita consumption, so it is endogenous to each particular model run. This is appropriate for 'non-marginal' policy problems such as climate change whose effects are potentially large relative to the economy as a whole (Stern 2007:39). In contrast to 'marginal' problems that are the conventional subjects of cost-benefit analysis, whether or not global emissions continue as 'business as usual' has the potential to result in very different paths for future global wellbeing. When a policy problem is non-marginal, conducting welfare economics must involve comparing the present value of welfare on these different paths directly, with present values calculated using the discount rate consistent with each path given its consumption growth rate (Stern 2007:50).

Not all climate policy questions are non-marginal, so endogenous and exogenous discounting both have a role in climate policy analysis. Quantitative analysis using endogenous discounting to compare different mitigation goals and choose an overall emissions reduction target can be followed by cost-benefit or cost-effectiveness analysis to choose emissions reduction projects to meet the chosen goal (Stern 2007:50). As the projects are marginal, they can be assessed using the exogenous discount rate prescribed in government guidelines.[5]

Having established that discount rates in Stern, Nordhaus and Garnaut's analysis are endogenous we can describe them further. Following the presentation in Stern (2007:50-52), we can illustrate the principles involved with the social welfare and utility functions used by Nordhaus and in the Stern Review.[6] Each uses an 'integrated assessment' model that links a macroeconomic model to a 'simple' climate model[7] through the environmental externality – changes in concentrations of greenhouse gases that cause temperature changes and reductions in output and welfare. With

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[5]Australian Government guidance on estimating the cost of abatement is due for publication by the Department of Climate Change and Energy Efficiency in 2011.

[6]Garnaut's quantitative modelling is similar but uses a utility function with multiple consumption goods, has a modelling horizon finishing in 2100 and models climate change impacts by estimating them exogenously and incorporating them as sector-specific shocks to a computable general equilibrium model of the Australian economy. For further details see Economic Modelling Technical Papers 1 and 5, Garnaut Climate Change Review (2008).

[7]Dietz and Asheim (2010:7) explain that the term 'simple climate model' came from the International Panel for Climate Change. In a simple model, each of the atmosphere, surface and deep oceans is modelled as a uniformly mixed box; in more complicated climate models the internal dynamics of these sinks are also modelled.

exogenous population (*N)*, social welfare (*W*) is the present value of the aggregate utility of per capita consumption:[8]

$$W = \int_{0}^{\infty} Nu(c)e^{-\rho t}dt \qquad (1)$$

where $\rho > 0$ is the rate of 'pure time preference'. This represents the rate at which future utility is discounted *purely* because it occurs in the future and regardless of its level. Substituting the isoelastic utility function we have

$$u(c) = \frac{c^{1-\eta}}{1-\eta} \qquad (2)$$

(which has limit $u(c) = \log(c)$ as $\eta \to 1$). The constant $\eta > 0$ plays up to three roles in integrated assessment models given this form of the utility function (see Dietz et al 2008: 10-11, Quiggin 2006). The first two roles are measuring preferences over the distribution of consumption within and across time. Here η, formally known as the elasticity of the marginal utility of consumption, measures how the marginal utility of consumption changes with increases in consumption. All values of η for which the function is defined imply that the marginal utility of consumption falls with higher consumption; a higher value of η implies that the marginal utility of consumption falls more quickly. In a social policy context with this utility function, this is equivalent to increased inequality aversion and a preference for more redistribution, both within and across generations. The third role of η is to measure relative risk aversion. In a stochastic model, higher η implies more disutility from exposure to risk.

The value of a unit of consumption at time *t* in the future relative to the present is measured by the social discount factor, λ:

$$\lambda = u'(c)e^{-\rho t} = c^{-\eta}e^{-\rho t} \qquad (3)$$

and the social discount rate is the proportionate rate of change of the discount factor:

$$SDR = -\frac{\partial\lambda / \partial t}{\lambda} \equiv -\frac{\dot{\lambda}}{\lambda} = \rho + \eta\frac{\dot{c}}{c} \qquad (4)$$

where the rate of growth of consumption ($\frac{\dot{c}}{c}$) is endogenous as discussed above. Before turning to the two approaches to assigning values to the exogenous parameters ρ and η, there are two things to note. First, the social discount rate has two parts. Even with zero *utility* discounting, the overall discount rate is positive for all permissible η when consumption is growing (Stern 2008:14). Positive consumption growth, coupled with aversion to intertemporal inequality,

[8]Nordhaus (2008:205, 208) uses a finite rather than an infinite sum, calculating social welfare over 600 years beginning in 2005.

means that increments to the consumption of the current, poorest, generation are judged more valuable, so the second term in Equation (4) discounts future *consumption*.

Second, with multiple goods, there will be multiple social discount rates. In particular, if 'services from the atmosphere' (maintaining a liveable climate) decline with increasing stocks of greenhouse gases while ordinary consumption grows, the social discount rate for atmospheric services would be negative while the consumption discount rate was positive (Stern 2007:60). We return to this point below.

Positive and normative approaches to endogenous discounting for climate policy evaluation

Whether or not values for ρ and η in the expression for the social discount rate are chosen with their ethical implications in mind, they embody ethical choices about risk and equity. A 'normative' approach to discounting chooses values for ρ and η through explicit consideration of their ethical implications, while a 'positive' approach chooses a combination of ρ and η so that the social discount rate matches an observed market rate of return. It is important to emphasise here that the normative approach of explicitly considering the ethical implications of ρ and η is not a purely introspective exercise conducted by sherry-sipping economist-philosopher kings. Both a normative and a positive approach to discounting for climate change policy have involved considering values inferred from observations. The two main differences between the two approaches are the *kinds* of observations considered relevant for when making social choices (which we discuss further below), and the *role* values inferred from observations can play when choosing ρ and η. Values from observation are decisive in a positive approach, but can only provide input into what is ultimately a matter of judgement in a normative approach.

Table 1 below summarises selected economists' approaches to discounting for climate policy analysis, their preferred values for ρ and η and (where they compare quantitative estimates of the costs and benefits of mitigation and specify preferred stabilisation concentrations) their climate policy prescriptions. While Nordhaus's choices for ρ and η have changed over time,[9] he chooses their values so that the social discount rate matches the historical long-run rate of return on equities (Norhaus 2001, 2008: 58, 61). Stern and Garnaut adopt a normative approach and lower discount rates. They argue (Stern 2007: Chapter 2; Garnaut 2008:18-21) that consideration of risk and equity is fundamental to choosing whether and how much to reduce emissions and that the ethical implications of parameters in the social discount rate need to be considered explicitly. In terms of policy prescriptions, Garnaut and Stern recommend strong and early mitigation action, while Nordhaus suggests weaker and more gradual emissions reductions. Both Stern and Nordhaus have revised their recommended stabilisation concentration downward since 2006.

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[9]Nordhaus and Boyer (2001) used a declining rate of pure time preference beginning at three per cent per year and declining to 1.25 in 2335, and a value of one for η. For a discussion of declining discount rates see Pearce et al (2006: chapter 13).

Table 1: Approaches to discounting for climate policy analysis and recommended mitigation policy, selected economists

Economist	Approach to discounting	Values for social welfare function parameters		Recommended stabilisation concentration of greenhouse gases (parts per million carbon dioxide equivalent (ppm CO_2-e))	Global average temperature increase above pre-industrial at equilibrium, using 'best estimate' climate sensitivity[a][b] (degrees Celsius)
		Rate of pure time preference, ρ (per cent per year)	η		
Stern – 2006 Review	Normative	0.1	1	Identified a range of 450-550[c]	2-3
Stern – post-Review	Normative	0.1	Indicated preferred value above 1[d]	Assessment[e] of risks narrowed Review range to 450-500ppm with below 500ppm considered desirable[f]	2-2.5[g]; lower end of range considered desirable
Garnaut	Normative	0.05	Used 1 and 2	450 or lower[h]	2 or lower[h]
Nordhaus (2008a)	Positive	1.5	2	Around 855[i]	4.9
Nordhaus (2010a,b)	Positive	Parameterisation yields discount rates similar to Nordhaus (2008a)		Around 550[i] ,following peak of around 745 in 2100[d]	3
Arrow (1995)	Normative	1	1.5[j]		
Dasgupta (2007)	Normative	Near zero	2-4		

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		Rate of pure time preference, ρ (per cent per year)	η		
Weitzman (2007)	Positive	2	2		
Weitzman (2010)	Possibly endorsing normative (2010:17)	0	3		

Notes:

See References for full details of sources.

(a)Climate sensitivity measures the change in equilibrium temperature associated with a doubling in atmospheric greenhouse gas concentrations; see section 3 below for further discussion.

(b)These estimates are from the International Panel on Climate Change's (IPCC's) 2007 Fourth Assessment Report which post-dates the Stern Review and the modelling in Nordhaus (2008a).

(c)See Hepburn and Stern (2009:40) for discussion.

(d)Stern (2008:23)

(e)Hepburn and Stern (2009:43).

(f)Stern (2008:7, 2010:39).

(g)Author's linear interpolation from IPCC (2007a:67).

(h)Garnaut (2008:280-1) notes that "there are advantages to Australia if the world commits itself at some time to a credible agreement that adds up to the objective of 400ppm [CO_2-e]. This would require agreement on and progress towards a 450 objective, with a subsequent lift in ambition".

(i)Nordhaus's modelling reports concentrations of CO_2. The contribution of other greenhouse gases to atmospheric concentrations depends on assumptions including their 'business as usual' trajectories; we use CO_2 equivalent concentrations from IPCC (2007a:67).

(j)Arrow (2007) uses 2.

Normative discounting

Among economists adopting a normative approach, there is near consensus on the rate of pure time preference (ρ). As discussed above, a positive value represents discounting the welfare of future people purely because they are born in the future. Both Stern and Garnaut followed a long line of philosophical thought in concluding that the characteristic of being born in the future should not be relevant for determining the weight someone's utility receives in a social welfare function.[10] They argued the only justification for non-zero rate of pure time preference is the tiny possibility that some non-climate-related catastrophe that means that future people do not exist at all. Both Stern and Garnaut used near- but non-zero rates of pure time preference (0.1 and 0.05 per cent per year respectively) to reflect this small possibility (Stern 2007:184; Garnaut 2008:19). Is there an inconsistency between these low rates of time preference and higher discount rates inferred from individual consumption and saving decisions? No. The first is a social rate and the second is a private one. Individuals can quite reasonably choose to discount their future wellbeing when choosing more chocolate over a trip to the gym, but simultaneously wish that collective decisions about problems with long-term, large-scale and potentially catastrophic outcomes are be made in a way that treats future generations the same as our own.

A normative approach to η, the other parameter in the social discount rate, is quite challenging. As it reflects three separate but related ethical ideas, the values suggested for η in each of these roles can be in conflict, and its value in any of the three roles is also contestable. There are two main ways to inform a normative choice of η: through 'thought experiments' about the ethical implications of different choices, and by inferring values from structures such as tax and transfer systems that provide information on societal preferences over inequality and risk.

Thought experiments are useful for making the choices of different values of η transparent. Stern (2008:15) discusses Okun's (1975) 'leaky bucket' experiments to make the implications of different choices for η more concrete. If person A is five times richer than person B, η equal to one implies a unit of consumption is worth five times as much to B than to A, so a transfer from A to B improves social welfare even if 80 per cent of the transfer was lost along the way.[11] With η equal to two, consumption is worth 25 times more to B and the transfer is worthwhile when up to 96 per cent is lost. Judgements about whether society accepts this trade-off or not can provide information about a value for η in social policy contexts.

As discussed above, a normative approach to discounting does not mean pure introspection, but does use caution in inferring ethics from observed behaviour because of the difficulties involved.

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[10]In economics in particular this argument goes back at least as far as Ramsey (1928) and has been supported by Pigou (1932) Harrod (1948), Sen (1961) and Solow (1974) amongst others (Stern 2007:37).

[11]From Equation (2) above, $\frac{\partial u}{\partial c} = \frac{1}{c^{\eta}}$ so for person A having *k* times the consumption of person B, the marginal utility of person A is $\frac{1}{k^{\eta}}$ times the marginal utility of person B. The interpretation of 'lost' funds is broad here and can include administration, losses through from raising taxation, and so on (Dietz et al 2008:12).

Dietz et al (2008:7-8) list four conditions necessary for revealed preferences to contain useful information about ethics for social policy decisions:

1. the observed behaviour reveals a unique preference;
2. the revealed preferences are 'true' preferences, based on full, correct information without decision-making errors;
3. the preferences are derived from a context that can map appropriately to the ethical judgement being made (that is, the preferences are 'contextually relevant'); and
4. the preferences are appropriate for social rather than private ethical choices.

When inferring preferences for climate policy evaluation, the last two of these conditions in particular pose challenges for inferring values from behaviour. Given that the aim is to infer ethical judgements for use in climate policy evaluation, preferences should be derived in a context that has at least some appropriate mapping to a global, long-term, risky and uncertain environmental problem with potentially catastrophic impacts. Economists adopting a normative approach to discounting have taken guidance from values of η inferred from tax and transfer systems, as they provide information about social preferences for the distribution of consumption within generations. Such empirical work has given a range of values for η including numbers less than one (Stern 2008:16). Cowell and Gardiner (1999:24-5) infer η from the United Kingdom personal income tax system, obtaining estimates of around 1.3 and 1.4 depending on the scope of taxes and transfers included. Evans (2005) investigates tax systems in 20 OECD countries, estimating η as 1.4, with a 95 per cent confidence interval of [1.2, 1.5].

Empirical work on risk aversion arguably offers less guidance on η. Observed individual and aggregate market behaviour is often inconsistent with the expected utility theory (Dietz et al 2008:12, Quiggin 2008:199), and values inferred from financial or insurance markets (see for example Gollier 2006) generally reveal individual rather than social preferences over risk. These individual preferences themselves exhibit a wide range of values depending on the context, from negative values (risk-seeking behaviour) for gambling and values of around 2 to 4 for insurance decisions (Dietz et al 2008).

A reading of their Reviews and subsequent major speeches suggests that Stern and Garnaut used both thought experiments and revealed social preferences to inform their choices of η (Stern 2007:52 2008:15-7; Garnaut 2008:19, 2010).[12] Both Stern and Garnaut note that η of two is very egalitarian compared to the amount of redistribution observed in tax and transfer systems (Garnaut 2010; Stern 2008:16). However, Garnaut used values of both one and two for η, arguing that a value of two "had been taken seriously in the reputed literature" (Garnaut 2010) while Stern (whose Review used a value of one) suggested that "with the benefit of hindsight" he

[12]While Stern (2007:52) notes that the choice of η is "essentially a value judgement" and considers thought experiments such as the one discussed above, he also describes his choice of η as being "in line with empirical estimates" (p.184) reviewed by Pearce and Ulph (1999), which include those derived from private saving behaviour.

would use a higher value of η as his central case (Stern 2008:23). Dasgupta's 2006 criticism of Stern's choice for η may have been influential here. Dasgupta argued (2006, 2007) that Stern's value of one required current generations to save an almost their entire incomes for future generations, which was absurd given the low incomes of much of the world's current population. However, Smith (2010) shows that, when using a more plausible macroeconomic model than that used by Dasgupta, saving rates consistent with Stern's original values for ρ and η are within the range of contemporary experience rather than close to 100 per cent.

At the core of Dasgupta's critique, and that of others including Nordhaus (2008a:137-142) and Porter (2009:24), is the argument that future generations will be much richer than us, so we should be cautious in investing too much in mitigation for their benefit. There are two main responses to this point. The first, discussed further in section three, is that there are "plausible worst cases" under which unmitigated climate change can result in falling per person consumption and welfare over time (Ackerman et al 2010; Asheim and Dietz 2010; Garnaut 2008:20). The small but non-negligible risk of potentially catastrophic outcomes, and the risks of very large differences in expected welfare between paths with different emissions levels, provide a rationale for normative discounting. However, the low social discount rates generally associated with a normative approach would seem to justify large sacrifices by the current generation if applied to other public investment decisions. We discuss another approach for capturing the non-marginal nature of climate change impacts below.

The second response to arguments that future generations will be too rich to require our investments in mitigation follows Neumayer (2007) in urging caution when interpreting single-good integrated assessment models. Neumayer (2007:300) notes that, with Stern's results, global output per capita in 2200 is estimated to be eight times higher than today if climate damages destroy 35.2 per cent of that year's output – but argues that to be sanguine about that loss given those projected higher incomes is to take the single-good nature of most integrated assessment models seriously.

If all that actually happened as a result of climate change was a large proportional fall in future global output, which remained at very high levels and roughly unchanged composition and distribution, it does indeed seem implausible and undesirable that we as the current generation should invest to avoid it. However, the different vulnerabilities of different economic sectors and regions to climate change impacts mean that expected climate damages will not leave the composition or distribution of output unaffected. While not captured in single-good quantitative models, it is the nature of the disaggregated impacts and the fact that climate change risks irreversible damage to essential, non-substitutable natural assets that would seem, perfectly understandably, to form the basis of many people's desire to take strong mitigation action. To list just two examples, a world of unmitigated climate change is expected to be a world in which the lower threshold for beginning accelerated disintegration of the West Antarctic ice sheet has been breached by the end of this century, and where irrigated output in the Murray Darling Basin has declined by more than 90 per cent relative to a no-mitigation case (Garnaut 2008:102, 130). The Stern and Garnaut Reviews rightly devote multiple chapters early in their Reviews to presenting disaggregated impacts, precisely because "a toll in terms of lives lost gains little in eloquence when it is converted into dollars; but it loses something, from an ethical perspective, by distancing us from the human cost of climate change" (Stern 2007:163). Sterner and Persson (2007) take a different approach to the same issue, modifying Nordhaus's integrated assessment model to include environmental as well as standard consumption goods. As the availability of environmental goods declines over time their relative price rises; the authors show that this 'relative price' effect can have as large an effect on the optimal amount of mitigation as changing the parameters in the social discount rate.

Before discussing consequences of and arguments for the positive approach to discounting, it is useful to point out that the choices above do not necessarily depend on a single ethical theory. While the overall approach of cost-benefit analysis is utilitarian, choosing to treat the wellbeing of future generations the same as our own and expressing some preference for redistribution are consistent with a number of different ethical perspectives.[13]

Positive discounting

Positive discounting chooses a combination of ρ and η to match an observed market rate of return. While there are numerous rates of return, these arguments tend to be made with reference to a rate of return on equities of around six per cent (Nordhaus 2008a; Weitzman 2007:707). Social discount rates under a normative approach to discounting have tended to be lower. Taking Equation (4) and substituting Garnaut's near-zero rate of pure time preference and real per capita consumption growth from the Garnaut or Stern Review base cases (1.3 per cent) the social discount rate is 1.35 and 2.65 per cent for η of one and two, respectively (Stern 2007:183; Garnaut 2008:19).[14]

Using higher discount rates significantly reduces the value of the benefits of avoiding future climate damages, and therefore the amount of mitigation judged to be welfare improving, other things equal.[15] As Stern (2007) and others have often pointed out, this reflects the simple fact that if we do not value future wellbeing very highly we are less likely to care about mitigation.

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[13] See for example Anand and Sen's (2000) work linking concepts of sustainable development with an approach to economic development emphasising human capabilities. Stern (2007:46-9) and Dietz et al (2008) discuss ethical perspectives relevant for the analysis of climate change including the approach embedded in standard welfare economics.

[14] As shown in Table 1 above, Weitzman (2010:17) may endorse a normative approach to discounting for climate change policy, but with a zero rate of pure time preference, consumption growth of two per cent and η of three, his social discount rate is six per cent.

[15] Dietz et al (2007:319) show the results of using Nordhaus's parameterisation of the social welfare function (pure time preference of 1.5 per cent and consumption elasticity of marginal utility of 2) in PAGE, the model used in the Stern Review. Naturally these parameters raise the discount rate and reduce estimates of the total cost of climate change relative to those used in the Stern Review. Smith (2010) and Nordhaus (2008) illustrate the same outcome in reverse (that is, using Stern's utility function parameters in Nordhaus's model reduces the discount rate and increases the optimal amount of mitigation). Smith applies Stern's utility function parameters to the economy as a whole, while Nordhaus applies the resulting lower discount rate to climate change investments only and evaluates welfare using his default utility function parameters (Nordhaus 2008:76).

There are two main arguments for using the positive approach of choosing a combination of ρ and η to match an observed market rate of return:[16]

1. market rates of return reveal information about trade-offs between current and future consumption which is relevant for parameterising the social discount rate; and
2. emissions reductions are investments and as such an efficient allocation of resources demands they earn same rate of return as other investments.

The first argument turns on whose preferences over what are relevant to the social discount rate for climate change policy. Arguing that market rates of return reveal information about trade-offs between current and future consumption relevant for the social discount rate in climate change policy is equivalent to arguing that the preferences revealed by short- to medium-term, personal or family choices about the distribution of consumption over time should be applied to considering a long-lived, non-marginal policy problem expected to have its most severe effects on people who cannot express their preference over the tradeoffs in today's markets. Applying Dietz et al's conditions discussed above, the preferences being revealed in these markets do not map well to the relevant policy context, and are preferences over private rather than social choices.

The second argument for positive discounting implies the private return on investment is equal to the social discount rate. There are multiple reasons to expect these rates to differ in an imperfect economy. The existence of externalities such as climate change is a case in point (Stern 2008:12).

Despite the differences between the positive and normative discounting, their numerical results can be similar. Garnaut (2008:20), Quiggin (2008:200), Stern (2008:13) and others have argued that *if* a positive approach to discounting is adopted, the appropriate market rate is the return on low-risk debt rather than equities. Very broadly, the opportunity cost of resources devoted to mitigation depend on what use they were diverted from (Dreze and Stern 1990). Stern (2008:13) argues that, as policy responses to reduce emissions are likely to involve changes in relative prices, mitigation is likely to divert relatively more resources from consumption than investment, so that observed rates associated with consumption rather than investment decisions are relevant. Real rates of return on low-risk debt are estimated at around 1.5 per cent (Stern 2008:13) or just above two per cent (Garnaut 2008:20, for Australian and US government bonds). These are close to the range of rates from a normative approach of around 1.3 – 2.6 per cent

[16]Nordhaus (2008:174) also argued that the 'business as usual' run of a climate model has to be our best guess of future emissions, so that choosing ρ and η to generate a social discount rate below the market rate overestimates capital accumulation and biases emissions upward. This argument is only relevant to climate policy models in which capital accumulation is endogenous, and may not be numerically significant. The model used in the Stern Review imported exogenous forecasts for world output and used a fixed saving rate of 20 per cent (Stern 2007:183), so business as usual emissions are emissions from a forecast of output based on the capital stock accumulated under expected market rates. Nordhaus's model does feature endogenous saving, but Figure 2 in Smith (2010:293-4) suggests that differences in the capital stocks accumulated with different parameterisations of the social welfare function are small in practice under the current default parameterisation of Nordhaus's model.

discussed above. Consequently Garnaut (2008:20) noted in his Review that his normative rates straddle an appropriate estimate of the positive discount rate.

An alternative approach: sustainable discounted utilitarianism

To conclude this section we discuss an alternative approach to intertemporal choice proposed by Asheim and Mitra (2010) and extended and applied to climate policy by Dietz and Asheim (2010). Dietz and Asheim (2010) are concerned about the consequences of positive utility discounting for the estimated benefits of mitigation, but also cautious that applying near-zero rates of pure time preference to investments outside the climate policy sphere might "contradict ethical intuition" by requiring the current generation to make substantial investments for the future even in the case of more marginal policy problems.

The authors' alternative, Sustainable Discounted Utilitarianism (SDU), is to introduce one additional constraint when evaluating social welfare. This constraint is that present wellbeing receives no weight if it exceeds projected future wellbeing. In the case that there are non-negligible risks that climate change impacts reduce future consumption below today's levels, this rule excludes the disutility of current investment in abatement, and so increases the net benefits of mitigation. When consumption rises over time the rule collapses to a standard discounted utility approach. Dietz and Asheim show that the two rules (SDU and discounted utility) produce different policy prescriptions in a modified stochastic version of Nordhaus's integrated assessment model. Under plausible alternative specifications for key climate variables (discussed further in section 3 below), unmitigated climate change causes a non-negligible probability that consumption falls over time. SDU recommends more mitigation than discounted utility approaches under these conditions. Importantly, this is robust to the choice of values for ρ and η, with the difference in optimal mitigation remaining for discount rates of up to five per cent (the highest analysed). The authors see this work as a first effort in applying recent advances in theories of intertemporal choice to climate change policy and argue that their initial results provide a strong rationale for expanding basis of climate change policy evaluation to include SDU.

3. Approaches to risk and uncertainty

While the risks and uncertainties around the costs and benefits of mitigation are both large, those around the benefits of avoiding damages are orders of magnitude larger (Dietz 2007). This is because many of the options for achieving sizeable emissions reductions exist today, and so at least have known current costs, while estimating the benefits of moving away from a business as usual emissions trajectory involves estimating the benefits of avoiding the impacts of temperatures that humans have never experienced, using a causal chain from emissions to impacts in which each relationship is subject to substantial uncertainty.

A central part of the Garnaut and Stern Reviews' case for strong and early mitigation action is the insurance value of reducing exposure to risks of experiencing some of the more serious impacts of climate change (Stern 2007:38; Garnaut 2008:271). Reading Nordhaus (2008a), who advocates weaker and more gradual action to reduce emissions, one finds much less emphasis on risk and its implications for choosing climate change policy. It is natural to ask whether this difference contributes to the economists' different policy positions. As discussed above, different approaches to discounting are clearly important for their different prescriptions: discounting the future benefits of mitigation less heavily will always imply stronger and earlier mitigation action, other things equal. While Nordhaus (2008a:168-9) argues that the approach to discounting is the key driver of Stern's "radical" policy, others disagree. Heal (2009:18) notes that use of a low social discount rate is only one of three determinants of whether or not an economic evaluation of climate change recommends strong and early action. The others are incorporating environmental goods directly into the utility function (as discussed above), and the treatment of risk and uncertainty – with much recent work suggesting that the choice of approach to risk is as important as the approach to discounting in assessing mitigation policy. To understand the relative importance of approaches to risk and discounting in determining climate policy prescriptions it is necessary to understand the approach to risk and uncertainty as well as discounting in the models used by Stern and Nordhaus. This section summarises the treatment of risk in both Policy Analysis of the Greenhouse Effect (PAGE) (used in the Stern Review) and Nordhaus's Dynamic Integrated model of Climate and the Economy (DICE), showing how different approaches can produce very different projections for consumption and welfare under business as usual climate change, and therefore different optimal policies. We describe the 'residual' risks inherent in Nordhaus's recommended climate policies and compare these to the climate policy recently agreed by the international community. The section concludes by considering the Garnaut Review's approach to risk and uncertainty in the context of Stern's and Nordhaus's approaches.

Stern and PAGE

PAGE is a stochastic model developed by Chris Hope (2006) and selected for the Stern Review because of its many desirable features but especially its treatment of risk (Stern 2007:174, 659). Thirty-one key inputs are stochastic, with the Review taking 1000 Monte Carlo draws. Density functions for the stochastic parameters are calibrated on the existing climate change literature so that the model is essentially meta-analytical (Dietz et al 2007a:317). In addition to modelling the impacts of 'gradual' (in a relative sense) climate change through a function linking temperature and reductions in output, PAGE also simulates the effects of large discontinuities in the climate system (such as melting of the Greenland and West Antarctic Ice Sheets) by introducing the probability of large losses in output once a threshold temperature is exceeded (Stern 2007:174). The Stern Review ran both a baseline and 'high' climate scenario, the latter of which explores natural feedbacks in the climate system accelerating climate change (Stern 2007:175).[17] Importantly, Stern's analysis of the benefits of reducing emissions conducts expected utility analysis: the Review calculated expected social welfare in the absence of mitigation action using the full probability density function for consumption (Stern 2007:174).

The expected utility approach makes it possible to:

[17]It is generally accepted that future climate change will reduce the ability of the carbon cycle to absorb emissions, but it is uncertain how the carbon cycle will react to climate change (IPCC 2007b:749-50).

1. examine the contributions of discounting and the use of full expected utility approach on estimated costs of climate change; and
2. investigate the effects of increasing risk aversion on the estimated costs of climate change.

Both of these form part of post-Review sensitivity analysis in Dietz et al (2007a).

In the first exercise, the authors find that moving from an 'all modes' approach (selecting the mostly likely value for each stochastic parameter) to full expected utility analysis increases the mean total cost of climate change in the baseline climate scenario in PAGE by 7.6 percentage points, while raising the pure rate of time preference from the Stern to the Nordhaus value results in a 7.8 percentage point fall in mean total costs same scenario. They conclude that the treatment of risk and uncertainty can be as important for the estimated costs of unmitigated climate change as the approach to discounting.

Exercise (2) is interesting because η links the approach to discounting and the approach to risk in PAGE. As discussed above, this single parameter represents all three of inter- and intra-temporal inequality aversion and risk aversion. Increasing η raises the discount rate, but also the disutility from exposure to risk, so has an a priori ambiguous effect on optimal mitigation policy. Dietz et al (2007a:319) show that, in PAGE, the risk aversion effect eventually dominates the inequality aversion effect for the Review's high-climate sensitivity scenario. Weitzman (2010:20) demonstrates the same result in an illustrative model with limited economic dynamics.

***Nordhaus*[18]**

DICE-2007 is the fifth version of a deterministic climate-economy model developed by Nordhaus and collaborators (Nordhaus 2008a:xii). It evaluates social welfare in the absence of mitigation action as the utility of consumption where parameters take their most likely values (Nordhaus 2008a:134). Like PAGE, DICE models both the impacts of (relatively) gradual climate change and the effects of large discontinuities in the climate system – indeed, Nordhaus pioneered proxying catastrophe damages with probabilistic large output losses as described above (Dietz et al 2007a:315).

While the standard version of DICE excludes risk, Nordhaus (2008a:123-47) recently incorporated a degree of risk by creating a version of the model with some stochastic parameters. He selects eight parameters that previous work has suggested are important drivers of model outputs (including the growth rate of total factor productivity, the sensitivity of temperature change to changes in greenhouse gas concentrations and the sensitivity of reductions in output to temperature changes), assumes normal distributions, and takes 100 Monte Carlo draws.[19] His surprising finding is that his deterministic analysis using the most likely values for all uncertain

[18]The author is grateful to Simon Dietz for his very helpful comments on an earlier draft of this and the next section.

[19]The remaining six parameters are the exogenous rate of decarbonisation of output, the intercept of the damage function, the price of a 'backstop technology' for reducing emissions (conceptually, the marginal cost of the last unit of emissions reduction (Dietz and Asheim 2010:9)), the asymptotic global population, a carbon cycle coefficient and the total stock of fossil fuels (Nordhaus 2008: 127).

parameters is a good approximation to the outcomes under expected utility analysis (2008:28).[20] This likely informed his (2008:168-9) claim that it Stern's approach to discounting that drives his different policy prescription.

Nordhaus's finding that uncertainty does not matter for climate policy prescriptions differs not only from the results from PAGE discussed above, but from three pieces of recent work examining the effects of uncertainty on climate policy prescriptions. Recent work by Ackerman et al (2010), Dietz and Asheim (2010) and Weitzman (2010) demonstrate that the sanguine projections of the only modest disutility of unmitigated climate change from integrated assessment models such as DICE are sensitive to the combined effect of two key climate parameters. These are the 'temperature sensitivity coefficient' that measures the change in equilibrium temperature associated with a doubling in atmospheric greenhouse gas concentrations, and the coefficient in the 'damage' function that determines the relationship between temperature changes and output losses from climate change.

While both temperature sensitivity and the damage function coefficient are very important for the welfare effects of unmitigated climate change, there is much more evidence on values for the former (Ackerman et al 2010:1662). Temperature sensitivity has been the subject of a large amount of empirical research, with the International Panel on Climate Change's (IPCC's) (2007b) review of estimates finding a mostly likely value of 3 degrees Celsius, and a two-thirds probability of lying between 2 and 4.5 degrees. Because of uncertainty about feedbacks in the climate system, all of the 18 probability density functions reviewed have a positive skew or 'fat right tail' (Dietz and Asheim 2010:10). In contrast, the relationship between temperature changes and damages for large increases in global average temperature is arguably an area of radical uncertainty, depending on the response of biophysical systems to warming and second-round socio-economic responses to climate change impacts, all of which are extremely uncertain. In the Stern Review, PAGE draws an exponent for the function from a triangular distribution with a minimum of 1, mode of 1.3 and a maximum of 3, which provides small chances of damages increasing very rapidly with changes in temperature (Dietz et al 2007a:314). DICE uses a quadratic damage function, but the justification for quadratic damages is scant.[21] While this functional form may be satisfactory for small temperature increases, its implications for large temperature changes are unconvincing. In particular, Ackerman et al and Weitzman independently show that, with quadratic damages, only around half of global output is lost when *global average* temperatures reach 19 degrees Celsius above pre-industrial levels (Ackerman et al

[20]A second surprising finding is that the social cost of carbon (that is, the total change in welfare, now and in the future, caused by emitting an extra unit of greenhouse gases today) calculated using 'most likely' parameter values is similar to but *higher* than the expected social cost of carbon calculated from the stochastic model (Nordhaus 2008:134). This would appear to be driven by the choice of a normal distributions rather than right-skewed distributions that characterise many climate parameters; as discussed above, Dietz et al (2007) find that effects of emissions on welfare rise monotonically with the move from most likely parameter values to full expected utility analysis.

[21]To quote Dietz and Asheim (2010:11) "there has never been any stronger justification of the assumption of quadratic damages than the general supposition of a non-linear relationship, added to the fact that quadratics are a familiar form to economists, with a tractable linear first derivative".

2010:1660, Weitzman 2010:14). Weitzman's (2010:8) discussion of the potential for a range of catastrophic impacts associated with much lower temperature increases provides a good illustration of why this result, and the damage function that produced it, seem extremely conservative.

Ackerman et al examine the sensitivity of DICE's results to the distributions for temperature sensitivity and the damage function coefficient. They replace the normal distributions in Nordhaus's sensitivity analysis with a lognormal distribution fitted to the IPCC likelihood statements (for temperature sensitivity) and a triangular distribution (for the damage function coefficient) and examine the effects on consumption and utility in a no-mitigation scenario using Nordhaus's discount rate parameters (ρ=1.5 and η=2). While varying each of the temperature sensitivity and damage function coefficient independently has only modest effects on optimal policy (Ackerman et al 2010:1662), there are "plausible worst cases" featuring both high temperature sensitivity and a high sensitivity of damages to temperature changes in which both utility and consumption per capita collapse in a no-mitigation scenario. Dietz and Asheim (2010) run Nordhaus's stochastic version of DICE with similar modifications to that of Ackerman et al. They replace Nordhaus's normal distributions with a lognormal distribution for the temperature sensitivity coefficient and a probabilistically steeper damage function and also find non-negligible probabilities of unmitigated climate change causing falling per capita consumption. Indeed, the probability that consumption was higher in the previous decade reaches around 80 per cent at the start of the 23rd century in a no-mitigation scenario. Weitzman (2010) constructs a "baby" model without dynamics and demonstrates that use of a quadratic damages function and a normal distribution for temperature sensitivity can seriously underestimate the welfare losses from unmitigated climate change.

In contrast, Nordhaus's own investigation of uncertainty, using small-sized Monte Carlo runs and normal distributions for the parameters, overlooks these extreme outcomes (Ackerman et al 2010:1659; Weitzman 2010:23). As a result Nordhaus concludes that deterministic analysis is a close match for stochastic analysis in climate policy evaluation.

Nordhaus's 'optimal' climate policy and 'climate responsible' emissions

At Cancun last December the Conference of the Parties to the United Nations Framework Convention on Climate Change agreed in a consensus decision (the 'Cancun agreements') that it was desirable to hold temperature increases to below two degrees Celsius on pre-industrial levels (United Nations 2010). DICE indicates that this policy is *welfare reducing*: it would be better for global wellbeing to do absolutely nothing to reduce emissions (Nordhaus 2008a:82). A more recent analysis using RICE, a regionally disaggregated version of DICE, finds that meeting the two degree temperature goal would be welfare improving but that stabilisation at higher concentrations of greenhouse gases would be preferable (Nordhaus 2010a). Nordhaus's exclusion of climate scenarios such as high climate sensitivity and very high damage function curvature provide one possible reason for the divergence between his policy prescriptions and the climate goals of the international community: global leaders may be placing weight on reducing the risk of extreme outcomes that are not possibilities in the standard versions of DICE and RICE. Leaders may well also be applying one of the many ethical perspectives and frameworks other than that of discounted utilitarianism. Economic analysis supportive of Nordhaus's approach can tend to focus on its rationale rather than the implications for global emissions and the associated consequences (for example Porter 2009). It is therefore interesting to present and compare the characteristics of and risks associated with Nordhaus's preferred climate policy and paths consistent with meeting the international community's two degree temperature goal.

The policy recommended by DICE-2007 leads to atmospheric concentrations of carbon dioxide rising to nearly 660ppm by the end of next century, a level Nordhaus reports as causing an increase in global temperature of 3.5 degrees Celsius above 1900 levels by 2200 (Nordhaus 2008a:83,103). The climate science underpinning DICE-2007 is based primarily on the IPCC's 2001 Third Assessment Report (Nordhaus 2008a:38). The IPCC's Fourth Assessment Report (finalised after the DICE-2007 modelling design was completed) suggests the most likely long-term temperature increase associated with Nordhaus's recommended concentration is 4.9 degrees on pre-industrial levels (Nordhaus 2008a:53; IPCC 2007a:67); the increase on 1900 levels would be very similar.[22] Even a global average temperature level resulting from a 3.5 degree temperature increase from 1900 levels is significantly above the relatively stable temperatures of the last 11,000 years that have contributed to the development of human civilisation as we know it (Zalasiewicz et al 2008).

The risks associated with the DICE-2007 'optimal' policy are very large. An increase of 3.5 degrees above 1900 levels, equivalent to around 3 degrees on 1990, is the bottom of the 'tipping point range' for switching eight of the Earth's subsystems into different states (Garnaut 2008: 271). While the threshold temperatures for these impacts cannot be known with certainty, Nordhaus published his policy recommendation in the same year that Lenton et al identified an increase of three degrees on 1990 levels as the bottom of the tipping point range for each of the melting of the west Antarctic ice sheet; disruption of the Atlantic thermohaline circulation; disruption of the El Nino – Southern Oscillation; disruption of the Sahara/Sahel and West African monsoon; dieback of the Amazon rainforest and dieback of boreal forest. The threshold for melting of the Arctic summer sea ice and the Greenland ice sheet was estimated to be less than two degrees Celsius above 1990 levels.

RICE-2010 incorporates scientific findings included in the IPCC's Fourth Assessment Report. Using this model, Nordhaus finds that meeting the two degree temperature goal is welfare improving, but that stabilisation at around 450ppm CO_2, equivalent to around 550ppm carbon dioxide equivalent, (CO_2-e) is preferable (Nordhaus 2010b:6; IPCC 2007a:67). Given the positive skew of the probability distribution for climate sensitivity discussed above, there is a small but significant

[22]The IPCC Fourth Assessment Report documents and the Garnaut Climate Change Review used a 1990 baseline, which is the average of 1980-1999 temperatures. The IPCC (2007a:45) advises that 0.5 degrees Celsius should be added to temperatures using the 1990 baseline to express the change relative to the period 1850-1899, often referred to as 'pre-industrial'. The DICE-2007 model uses a 1900 temperature baseline which is an average of 1890-1910 temperatures (Nordhaus 2008a:91).

probability that this policy will result in the temperature breaching the bottom of the tipping point range discussed above (Garnaut 2008: 272).

The impacts from breaching these tipping points are the certainly the kinds of “dangerous anthropogenic interference with the climate system” that the United Nations Framework on Climate Change aims to avoid (United Nations 1992). Examining the relationships between temperature changes and climate change impacts to create a climate policy goal informed by science and consistent with the Convention led to the choice of a temperature ‘guardrail’ of holding increases to two degrees Celsius on pre-industrial levels (EU Climate Change Expert Group 2008:8). This goal was adopted by the European Commission in 1996 and formally by the international community in the Cancun Agreement of December 2010 (EU Climate Change Expert Group 2008:8; United Nations 2010:2). Stabilising concentrations of greenhouse gases at a concentration equivalent to 450ppm CO_2-e is estimated to provide a 50 per cent chance of limiting temperature increases to two degrees above pre-industrial levels (see Richardson et al 2009:18). However, changes in the expected relationships between impacts and temperatures (Figure 1) mean that, if the costs of meeting the temperature goal were unchanged, the preferences that motivated the choice of the two degree guardrail would now point to a lower temperature goal (Figure 1). This arguably motivates the inclusion of a commitment to examine the two degree temperature goal in the Cancun agreements (United Nations 2010:2, 22).

As concentrations depend on the stock of greenhouse gases in the atmosphere (Stern 2007:325), multiple pathways for the flow of emissions are consistent with achieving stabilisation at 450ppm CO_2-e. Each of these requires global emissions to peak and then fall, with those delaying the peak requiring sharper subsequent rates of emissions reductions (United Nations Environment Program 2010:11-2). ‘Climate responsible’ paths for stabilisation at 450ppm CO_2-e involve an earlier peak so that rates of emissions reductions after peaking remain at levels considered technically and economically feasible (Stern and Taylor 2010:9, 24-6). These paths require global emissions to peak in the middle of this decade, fall to around 40-44 billion tonnes of CO_2-e by 2020 and reach around 16 billion tonnes by the middle of this century (Stern and Taylor 2010:15, 25). In contrast, emissions under Nordhaus’s policies grow throughout this century in DICE-2007 and for around half of this century in RICE-2010 (Nordhaus 2008a:100; 2010a:11723).

Garnaut

To conclude this section we compare Garnaut’s approach to risk and uncertainty with that of Stern and Nordhaus. Garnaut’s ethical approach and emphasis on the importance of risk and uncertainty in determining climate policy are similar to Stern’s, but his formal modelling is deterministic. Instead of Stern’s formal expected utility analysis, Garnaut examines the consequences of radical uncertainty explicitly but outside of his formal modelling framework.

Figure 1: The relationship between impacts and expected global average temperature increases

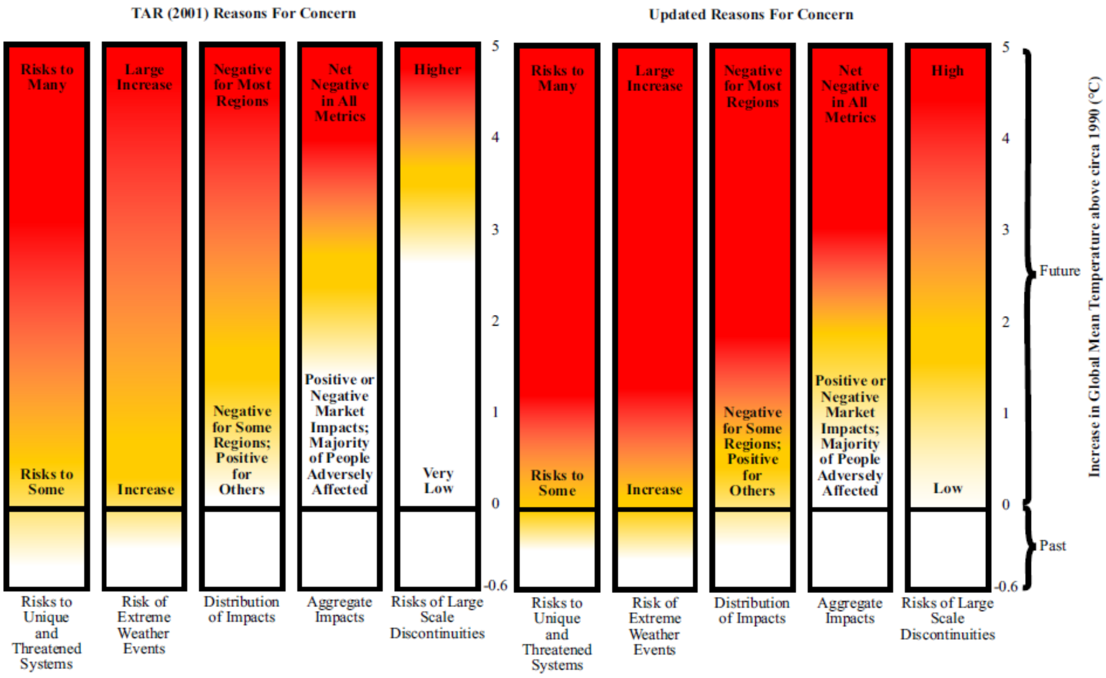

Fig. 1. Risks from climate change, by reason for concern—2001 compared with updated data. Climate change consequences are plotted against increases in global mean temperature (°C) after 1990. Each column corresponds to a specific RFC and represents additional outcomes associated with increasing global mean temperature. The color scheme represents progressively increasing levels of risk and should not be interpreted as representing "dangerous anthropogenic interference," which is a value judgment. The historical period 1900 to 2000 warmed by ≈0.6 °C and led to some impacts. It should be noted that this figure addresses only how risks change as global mean temperature increases, not how risks might change at different rates of warming. Furthermore, it does not address when impacts might be realized, nor does it account for the effects of different development pathways on vulnerability. (*A*) RFCs from the IPCC TAR as described in section 1. (*B*) Updated RFCs derived from IPCC AR4 as supported by the discussion in section 2. (Reproduced with permission from Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Figure SPM-2. Cambridge University Press.)

Abbreviations in Figure notes: RFC = 'reasons for concern'; TAR= Third Assessment Report; AR4=Fourth Assessment Report.
Source: Smith et al (2009:4134).

Garnaut (2008:245-275) calculates the net benefits from stabilisation at 550 and 450ppm CO_2-e based on median 'market impacts (those that could be estimated in or introduced exogenously into a computable general equilibrium model) and makes an explicit judgement outside of his quantitative modelling framework about the implications of the risks and non-market impacts (such as species and biodiversity loss) associated with stabilisation at 550ppm. As discussed above, these include higher risks of crossing globally significant tipping points, including initiating large-scale melting of the Greenland ice sheet (Garnaut 2008:271-2). His finding that global action to stabilise concentrations at 450ppm or lower is in Australia's national interest has been formally accepted by the Australian Government (2008:li).

Both Stern's and Garnaut's approaches to risk and uncertainty are useful and appropriate. Each place risk and uncertainty at the centre of their frameworks for choosing climate policy. There are two benefits of Stern's formal expected utility approach. The first is a political economy argument that the results of quantitative analysis can take on a stature in policy deliberations that qualitative analysis generally does not seem to match. Reflecting on the Review, Garnaut (2010) says that the costs and benefits the Review quantified "were treated more seriously" than those that were not. A second benefit of quantification is that the attempts, while preliminary, can motivate further research that improves our ability to conduct quantitative analysis that deals appropriately with risk and uncertainty. Much of the valuable recent research discussed in this paper, in particular that of Weitzman, Dietz and Asheim and Ackerman et al, was probably motivated in part by the desire to improve quantitative estimates of the benefits of mitigation in a stochastic framework. In favour of Garnaut's approach is the downside risk associated with the greater weight that quantitative analysis can acquire – that, despite the cautions of their creators, their numbers are taken *too* seriously given the difficulty of quantification. As both Stern and Garnaut stress (Stern 2007:43-4188-9, Garnaut 2008:xxiii, 247), these difficulties are profound because climate change tests the limits of quantitative welfare analysis.

4. Conclusion

We close with some remarks on economic assessments of mitigation policy and the implications for economists contributing to public debate on climate change policy. Nordhaus (2008a:166, 168-9) notes that while all economic studies support imposing immediate restraints on greenhouse gas emissions, they differ in the amount of recommended mitigation, and argues that the approach to discounting drives the difference between his policy and Stern's. In fact, a low social discount rate is one of three changes that have been identified as sufficient to reverse DICE's prescription of modest, gradual mitigation, the others being the inclusion of environmental services in the utility function (Sterner and Persson 2007), and the use of more plausible specifications for the damage function and probability distribution function for the temperature sensitivity coefficient in a stochastic setting (Ackerman et al 2010, Dietz and Asheim 2010).

More recently, Nordhaus (2010a) finds that limiting temperature increases to two degrees Celsius is welfare-enhancing relative to business as usual, but not optimal. This means that now each of Stern, Garnaut and Nordhaus find that immediate action consistent with meeting the international community's two degree temperature goal is worthwhile. While it is too early to describe the prescription of strong and early mitigation action as a 'consensus' economic view, it does seem reasonable to suggest that a growing body of recent, rigorous economic analysis concludes that mitigation consistent with the goals of the international community would improve global welfare.

This has some important implications for economists and their contribution to public debates on climate change policy. It is no longer tenable to dismiss economic analysis recommending stabilisation at 450ppm CO_2-e as 'purely' an artefact of the use of low social discount rates. Equivalently, a philosophical commitment to prescriptive discounting at high rates is not sufficient to support a gradual restraint of emissions and its associated high stabilisation concentrations of greenhouse gases. Indeed, to maintain the view that stabilisation at high levels is optimal, policy would need to give little or no weight to plausible, globally significant risks and uncertainties despite credible findings that accounting for these implies dramatically lower optimal emissions pathways (and deeper emissions reductions) – even at rates of return used by Nordhaus.

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