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Article (Accepted version) (Refereed)

Original citation:
Dietz, Simon, Hope, Chris and Ranger, Nicola (2007) *Some economics of 'dangerous' climate change: reflections on the Stern review.* Global Environmental Change, 17 (3-4). pp. 311-325. ISSN 0959-3780

DOI: 10.1016/j.gloenvcha.2007.05.008

Some Economics of 'Dangerous' Climate Change: Reflections on the *Stern Review*

Published in *Global Environmental Change*, **17(3-4)**, 311-325, 2007

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[1] We are grateful to Alex Bowen, Paul Baer, Eric Neumayer, Nicholas Stern, Dimitri Zenghelis and two anonymous referees for comments on earlier versions of this paper, and to Richard Tol for a helpful discussion. Chris Hope acknowledges the financial support of OFGEM.

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Abstract

The Stern Review on the Economics of Climate Change concluded that there can be “no doubt” the economic risks of business-as-usual climate change are “very severe” (Stern, 2006, p188). The total cost of climate change was estimated to be equivalent to a one-off, permanent 5-20% loss in global mean per-capita consumption today. And the marginal damage cost of a tonne of carbon emitted today was estimated to be around $312 (p344). Both of these estimates are higher than most reported in the previous literature. Subsequently, a number of critiques have appeared, arguing that discounting is the principal explanation for this discrepancy. Discounting is important, but in this paper we emphasise that how one approaches the economics of risk and uncertainty, and how one attempts to model the very closely related issue of low-probability/high-damage scenarios (which we connect to the recent discussion of ‘dangerous’ climate change), can matter just as much. We demonstrate these arguments empirically, using the same models applied in the *Stern Review*. Together, the issues of risk and uncertainty on the one hand, and ‘dangerous’ climate change on the other, raise very strongly questions about the limits of a welfare-economic approach, where the loss of natural capital might be irreversible and impossible to compensate. Thus we also critically reflect on the state-of-the-art in integrated assessment modelling. There will always be an imperative to carry out integrated assessment modelling, bringing together scientific ‘fact’ and value judgement systematically. But we agree with those cautioning against a literal interpretation of current estimates. Ironically, the *Stern Review* is one of those voices. A fixation with cost-benefit analysis misses the point that arguments for stabilisation should, and are, built on broader foundations.

Keywords

Climate change; cost-benefit analysis; catastrophic climate change; dangerous climate change; integrated assessment; risk; uncertainty

1. Introduction

The Stern Review on the Economics of Climate Change concluded that there can be “no doubt” the economic risks of business-as-usual (BAU) climate change are “very severe” (Stern, 2006, p188). The total cost of climate change was estimated to be equivalent to a one-off, permanent 5-20% loss in global mean per-capita consumption today. And the marginal damage cost of a tonne of carbon emitted today was estimated to be around $312 (p344). These estimates are high in relation to the previous literature, as commentaries on the *Review* have already pointed out (e.g. Nordhaus, 2006; Tol and Yohe, 2007). For instance, in his review of estimates of the marginal damage cost of a tonne of carbon emitted approximately today, Tol (2005) finds that the mean estimate from the wider literature – peer-reviewed and otherwise – is $122/tC, while considering only the peer-reviewed literature it is $43/tC. Indeed, since the first wave of cost-benefit analyses (CBAs)[2] of climate policy in the early-mid 1990s (e.g. Cline, 1992; Fankhauser, 1995; Maddison, 1995; Manne *et al*., 1995; Nordhaus, 1991, 1994a; Peck and Teisberg, 1992; Plambeck and Hope, 1996; Tol, 1997), most have yielded low estimates of the cost of climate change and recommended modest optimal greenhouse gas (GHG) emission reductions (with the notable exception of Cline, 1992).

Of course, the conclusions of this wider literature have been subject to criticism. Of the many arguments made, we will engage with two in this paper. The first is that most CBA studies are limited to a relatively narrow set of the most measurable impacts, which turn out to be (not entirely by coincidence) marginal to future economic development. They are particularly weak at representing the potential that does seem to exist for costs to escalate rapidly at high levels of global warming. This is linked with a technical economic concern, namely that the most aggregated cost-benefit models implicitly assume perfect substitutability between natural capital and other forms of capital (highlighted by Neumayer, 1999). But climate damage could, it is argued, deplete and degrade so-called ‘critical’ natural capital, which is essential for human development and the loss of which can neither be reversed nor be compensated by increasing production and consumption of other goods and services. In this paper, we connect these concerns to recent discussions about ‘dangerous’ climate change (see Schellnhuber *et al*., 2006). The second is that CBA studies inadequately represent the uncertainty that surrounds the impacts of climate change (e.g. Azar, 1998; Roughgarden and Schneider, 1999; various contributions to *Climatic Change*, **56(3)**). These two criticisms are related, since one of the principal sources of uncertainty is that surrounding the likelihood of catastrophic climate damages and the economic consequences of high levels of warming more generally.

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[2] We use the term CBA quite loosely in this paper to capture any studies, which estimate the monetary costs of climate change/benefits of climate-change mitigation, the costs and benefits of mitigation together, or other closely related issues.

There are other criticisms. Traditionally, much of the focus has been on high discount rates (e.g. Azar and Sterner, 1996; Broome, 1992; Cline, 1992). We do not devote this paper to discounting, since it is well known that the monetary cost of future climate change is highly sensitive to it (most recently demonstrated by Guo *et al*., 2006). However, we will estimate the sensitivity of the *Stern Review* calculations to increases in the components of the social or consumption discount rate, in order to put other factors in context. A further set of criticisms has been levelled at the welfarist ethical framework underpinning CBA. Along this line of reasoning, it may be unethical to impose environmental damage on future generations, as compensation by way of increased consumption of non-environmental goods is inadequate in principle (e.g. Barry, 1991; Spash, 1994). This also amounts to postulating that natural resources are non-substitutable, but on an *a priori* basis. Legitimate as alternative ethical frameworks are, in this paper we adopt an avowedly welfarist perspective.

The primary purpose of this paper is to show that the *Stern Review's* estimates depend heavily on its relatively comprehensive treatment of risk and uncertainty on the one hand, and on its attempts to represent low-probability/high-impact damage scenarios on the other. Moving from the least to the most encompassing modelling approaches in these respects makes a very substantial difference to the overall estimate of climate damage. Moreover, this difference is of a comparable magnitude to the differences caused by alternative discounting assumptions, with the obvious and important proviso that, in most of this analysis as in most others, a high (utility) discount rate renders largely irrelevant in present-value terms any serious consequences of climate change in the far-off future. That is to say, a low (utility) discount rate is almost always needed for uncertain, dangerous climate change in the far-off future to matter.[3]

In section two, we discuss in more detail how CBA studies can model 'dangerous' climate change. We also survey concerns about how CBA studies treat risk and uncertainty. This inevitably means that we must mention discounting, since the estimation of social welfare losses due to climate change usually involves the application of the same utility function to the distribution of consumption across time, space and risks or states of the world. Throughout section two, we clarify the assumptions of the *Stern Review's* IAM and welfare valuation and in section three, we provide additional details about them. Section four reports our results and section five provides a discussion.

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[3] On the other hand, we present some scenarios in this paper, in which the combination of the risk of very high climate damages and high risk aversion leads to high overall estimates, in present-value terms, even with a higher utility discount rate. More generally, if it could be demonstrated that the impacts of climate change in the short to medium term are very high, then the influence of the utility discount rate would be reduced.

2. Dangerous and uncertain climate change

2.1. Dangerous climate change in integrated assessment models

It has often been observed that the integrated assessment models (IAMs) used in cost-benefit studies are limited to a relatively narrow set of the most measurable impacts, a point systematically made by Downing *et al*. (2005). In particular, very few IAMs have been extended to cover large-scale, discontinuous changes to the climate system. And none have yet been explicitly extended to cover so-called 'socially contingent' impacts, which are large-scale, 'second-round' socio-economic responses to climate change like conflict and migration. Since there appears to be a correlation between the measurability of impacts and their potential magnitude, such that many of those we understand least have the potential to be highly damaging, we might reasonably conclude that most IAM studies are restricted in their capacity to simulate the potentially rapid escalation of climate damages as warming proceeds. While perhaps not the most likely scenario, such an escalation is plausible and thus its omission is serious, which is the basic source of a criticism levelled by Neumayer (1999). For him, CBA studies deny the possibility that GHG emissions are depleting and degrading natural resources, which are essential for human development and the loss of which can neither be reversed nor be compensated by increasing production and consumption of other goods and services. Technically, these are essential, non-substitutable natural resources, or 'critical' natural capital assets.

These arguments provide a point of contact between the cost-benefit tradition and the recent framing of climate impacts in terms of 'dangerous' climate change. Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) calls for stabilisation of atmospheric GHG concentrations such that 'dangerous anthropogenic interference' with the climate system is prevented (United Nations, 1992), so the term 'dangerous' is of both academic and political importance. Nevertheless, over fifteen years of debate on the meaning of dangerous climate change has resulted in many definitions (Dessai *et al*., 2004; Schneider and Lane, 2006). This is unsurprising, since what is dangerous is ultimately a value judgement. Thus global CBA of climate policy makes just one of many possible interpretations of danger. The value judgements it makes are based on preference-satisfaction utilitarianism, which is almost always made operational by aggregating all of the effects of climate change on to a single metric, consumption-equivalent welfare or utility. This is calculated for a representative consumer worldwide (i.e. one global, very long-lived consumer) and discounted across time-periods. Different consumers may represent different world-regions and different states of the world.

Dangerous climate change might then be defined as any process that produces losses in consumption-equivalent welfare, which are both rapid and large-scale relative to global trend consumption. What constitutes rapid and large-scale is arbitrary: there is no *a priori* basis for drawing the line between dangerous and 'non-dangerous' at any particular rate or level of welfare loss. Nevertheless, we can provide a little more clarity by focussing on the processes by which they are brought about. These are the very same large-scale, discontinuous changes to the climate system and rapid, large-scale socio-economic responses to climate change, which most IAM studies fail to incorporate. Without them, losses in welfare-equivalent consumption over the next two centuries are predicted to reach just a few percent of global output, relative to estimates without climate change. Given that trend growth in global consumption per capita is often projected to average around 1% per annum or more over the same time period, this is at most a very small 'blip' on the global growth path. With them, comparable losses can run into many tens of percent of global output, impacts which we might label 'dangerous'.

This demands a close examination of the pathways along which IAMs *can* simulate dangerous climate change, as we have defined it. Evaluating the *Stern Review* further requires that we understand to what extent its models did so. It is expositionally convenient (i.e. in terms of how they are actually represented by IAMs) to distinguish between three such pathways:

1. Rapid, large-scale impacts of gradual climate change;
2. Abrupt, discontinuous and large-scale positive natural feedbacks in the climate system that accelerate global warming;
3. Other abrupt, discontinuous and large-scale changes to the climate system that have more direct economic impacts.

The first comprises rapid, large-scale impacts of what we might call 'gradual' climate change. In the most aggregated IAMs like DICE (Nordhaus, 1994a) and PAGE (Hope, 2006), the latter of which was used by the *Stern Review*, this pathway is represented by a damage function that relates overall impacts, on consumption- or income-equivalent welfare[4], to an index of global mean temperature. Generally, this function is calibrated first through an estimate of overall impacts at 2.5°C or 3°C warming and second through an estimate of the functional form that traces impacts from zero warming, through the estimate

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[4] The relationship between consumption and income/output depends on the marginal propensity to save, which may be endogenous to the model or set exogenously. In the *Stern Review* modelling, the saving rate is a constant 0.2, so consumption-equivalent losses can simply be scaled to income-equivalent losses. However, the role of endogenous saving, and in turn investment, is potentially important. Reactions to gross saving could dampen the negative impacts of climate change, if agents wish to compensate for the faster depreciation of the capital stock due to climate change. On the other hand, it could amplify them, in the main because capital is less productive due to climate change and thus the rate of return on saving is lower. The effect on net saving, however, is unambiguously negative, because the positive incentive to offset capital depreciation nets out (Fankhauser and Tol, 2005).

for 2.5°C/3°C warming, and beyond to higher global mean temperatures. A very simple specification of the functional form, in this case with respect to 2.5°C warming, is as follows:

$$d(t) = \beta\left(\frac{T(t)}{2.5}\right)^{\gamma} \tag{1}$$

Where T is warming at time t, in terms of global mean temperature above pre-industrial, $d(t)$ is the economic damage caused by climate change expressed as a fraction of consumption or income, β is the consumption loss accompanying 2.5°C warming and γ is the damage function exponent.

IAM studies are in broad agreement that the impacts of climate change at 2.5°C-3°C warming are small in relation to trend growth in global consumption (i.e. growth forecast in a world without climate change, which may be exogenous or endogenous to the model). The 2001 IPCC *Third Assessment Report* (TAR) summarised the literature to that point, putting estimates roughly in the range of a 0% to 2% loss in gross world product (Smith *et al*, 2001). But for higher global mean temperatures, there is greater disagreement between studies and the possibility that impacts escalate rapidly. This is because the damage function exponent, γ, strongly affects such estimates. Figure 1 illustrates the differences between cost estimates, as a function of global mean temperature, for different values of γ. For simplicity, estimates are normalised to 2.5°C warming.

FIGURE 1 HERE

Figure 1 reflects the range that γ has taken in previous studies (e.g. Hope, 2006; Nordhaus, 1994a; Nordhaus and Boyer, 2000; Peck and Teisberg, 1992; Plambeck and Hope, 1996; Roughgarden and Schneider, 1999). Where γ equals 1 – i.e. impacts are a linear function of warming – 5°C warming reduces GWP by twice as much as 2.5°C warming, so damage is 2% of GWP at 5°C warming if β=1, 4% if β=2 and so on. However, where γ is set to 3, it brings about a loss around 8 times larger at 5°C than at 2.5°C, and increasing rapidly. At 6°C warming, the loss is 14 times as large. The PAGE model used by the *Stern Review* (Hope, 2006) draws γ from a triangular probability density function with a minimum of 1, mode of 1.3 and maximum of 3 (giving a mean of about 1.8). So there is a small likelihood of rapidly escalating economic impacts beyond those assumed by most other IAM studies (an exception is the sensitivity analysis of Peck and Teisberg, 1992, which also tests γ=3).

A major note of caution must be sounded at this stage: γ is essentially assumed, since the underlying impact studies on which IAMs are reliant become very sparse in the range of 4-5ºC warming and beyond. We possess some sector-specific evidence (see especially the review of Hitz and Smith, 2004), but this is certainly insufficient to illuminate the overall picture. There are a number of basic biological and physical principles indicating that impacts in many sectors will become disproportionately more severe with rising temperatures (Stern, 2006). On the other hand, estimates of γ in equation (1) are currently much less reliable than those of β (e.g. Mendelsohn, 2006).

For convenience, we treat the impacts of gradual climate change, pathway one, as distinct from the impacts of abrupt, discontinuous and large-scale changes to the climate system. In the set-up of a typical IAM, these changes, which have been called 'macro-discontinuities' (Smith *et al.*, 2001, p947), are further divided into two separate pathways. Pathway two comprises the large-scale release of GHGs from sinks, which constitutes a positive natural feedback to global warming by accelerating the overall atmospheric build-up of GHGs. A number of studies have considered the threat that climate change could pose for terrestrial biospheric and oceanic carbon sinks (e.g. Friedlingstein *et al.*, 2006, for terrestrial sinks and Orr *et al.*, 2006, for oceanic sinks), as well as whether the melting of permafrost and the warming and drying of wetland areas could produce large amounts of methane (e.g. Davidson and Janssens, 2006; Gedney *et al.*, 2004). More speculative is the release of methane from vast oceanic stores of gas hydrates (Hadley Centre, 2005). There would be direct economic impacts associated with these macro-discontinuities. For example, melting permafrost would damage Arctic infrastructure, assuming no adaptive measures. But in IAMs, the consequence of GHG sink releases is indirect: through the acceleration in the accumulation of atmospheric GHGs they induce and the consequences of the extra warming that results.

Abrupt, discontinuous and large-scale positive natural feedbacks are uncertain and as such have received virtually no attention in IAM studies to date. One exception is Ceronsky *et al.* (2005), which, in a sensitivity analysis, looks at the dissociation of methane hydrates and its consequences for the marginal damage cost of carbon. Another is the *Stern Review*, which specifies a high-climate scenario to take account of recent quantitative modelling of positive natural feedbacks. To be more precise, the scenario is based on recent estimates of a temperature-dependent weakening of natural carbon absorption (Friedlingstein *et al.*, 2006) and increased natural methane releases from permafrost and wetlands (using a probability distribution based on recent studies such as Gedney *et al.*, 2004). Together, these feedbacks add 0.4ºC to mean warming in 2100 compared with the *Review's* baseline-climate scenario, which replicates the range of warming projections in the IPCC TAR[5], and an additional 1.2ºC in 2200. The baseline-scenario estimates are 3.9ºC and 7.4ºC respectively.

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[5] The baseline-climate scenario includes a modest positive feedback, as indeed do most other IAM studies.

Pathway three comprises the other, wider class of macro-discontinuity in the climate system, such as a regional or global shutdown of the Thermohaline Circulation, rapid melting of the Greenland and West Antarctic Ice Sheets, transformation of continental monsoons or modification of the El Nino Southern Oscillation. These non-linear changes are difficult to predict, but are plausible given what is known about the chaotic nature of the climate system and past climate changes. If they did occur, these would have direct economic impacts. So far, only two IAMs have built the possibility of these kinds of macro-discontinuities into their core model structure. The pioneering estimates were included in DICE/RICE-99 (Nordhaus and Boyer, 2000). The *Stern Review* IAM, PAGE, also includes the risk of catastrophe. When global mean temperature rises to a threshold level (a minimum of 2°C above pre-industrial, mode of 5°C, and maximum of 8°C), the chance of large losses in GDP in the range of 5-20% begins to appear (minimum 5%, mode 10%, maximum 20%). This chance increases by an average of about 10 percentage points per °C rise in global mean temperature (minimum 1, mode 10, maximum 20).

$$d(t) = \zeta\theta(T(t) - T_{TRIGGER}) \tag{2}$$

Where ζ is the loss in GDP if a macro-discontinuity occurs, θ is the probability of a macro-discontinuity and $T_{TRIGGER}$ is the threshold global mean temperature, above which a macro-discontinuity becomes possible. Thus the risk of direct impacts from abrupt, large-scale and discontinuous climate change is modelled as a subjective joint probability. The probability density functions were calibrated on information presented in the IPCC TAR, although the TAR never addressed the issue directly. In particular, the TAR presented some evidence on $T_{TRIGGER}$, but almost none on θ and ζ, except for some order-of-magnitude quantification. In short, equation (2) is a genuine guesstimate, and that is why the ranges used for the parameters are so wide.

In summary, it is evident that some IAMs, such as the PAGE model used by the *Stern Review*, can model high-damage scenarios globally in at least one of three ways. But how can this be reconciled with the criticism that the very same models ignore the possibility of natural capital, which is essential and non-substitutable (Neumayer, 1999)? The essence of the critique is that the production and utility functions specified in CBA studies of climate policy derive from the tradition of ‘weak’ sustainable development, in which it is generally assumed that natural capital is perfectly substitutable (see Neumayer, 2003). But, in fact, CBA studies do not directly address the question of substitutability at all. Natural capital is not a separate argument in their production functions. Nor is it usually a separate argument in their utility functions (but see e.g. Tol, 1994). Instead, the impacts of climate change on the stock of natural capital enter the production and consumption calculus indirectly. To be precise, they in effect enter the production function as a multiplying coefficient, for example as follows:

$$Q(t) = \frac{1}{1+d(t)} A(t)K(t)^{\alpha} L(t)^{1-\alpha} \tag{3}$$

Equation 3 is a standard Cobb-Douglas production function in which output Q is a function of man-made capital K, labour L and (exogenous) technological progress A. α is the share of total output to man-made capital and $1-\alpha$ is the share of total output to labour. This is the production function used, for instance, in Nordhaus (1994a). Some IAMs like PAGE simplify the representation of production by taking an exogenous trend (e.g. Hope, 2006). Importantly, the total output available to the economy is multiplied down by climate damage $1/(1+d(t))$. This includes impacts on market sectors of the economy – an impact on production – and direct impacts on, for example, human health and ecosystems. The latter is a direct impact on welfare-equivalent consumption, but is indirectly treated as a loss in production.

Climate damage in equation (3) is the sum of equations (1) and (2), so it is perfectly feasible to simulate damages, which become so high under a plausible warming scenario that income is eventually dragged down to subsistence levels.[6] This can be interpreted as a scenario analogous to the depletion and degradation of critical natural capital due to GHG emissions. Admittedly, it is a very crude approximation. The problem can only be directly tackled once natural capital and its goods and services directly enter the production and utility functions respectively, such that their relative prices can rise to reflect their increasing scarcity. And it is a smooth function. So Neumayer (1999) is correct in a strict sense. But beyond this, the effect on policy of both approaches to the problem is broadly the same: i.e. stabilise atmospheric GHG concentrations at a low level to avoid damages of these magnitudes. The method employed by cost-benefit studies is indirect, but the basic modelling structure permits evaluation of the consequences of exceeding critical thresholds in the climate system, beyond which economic activity is severely threatened. In the limit, such analysis can be been extended to simulate a discontinuous damage function, whereby exceeding some climate threshold (indexed to global mean temperature) brings about very rapidly increasing damages (similar to the ‘hockey-stick’ function in Manne and Richels, 1995). Whether this is a plausible specification is an empirical question, although it is quite reasonable to then ask how sure we can be that is implausible. So it is to uncertainty that we now turn.

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[6] Indeed, if damages are not bounded from above, then income can become negative. This is discussed in more detail below, especially in footnote 7.

2.2. Modelling uncertainty

All the links in the chain between GHG emissions and the economic impacts of climate change – each of which needs to be parameterised in an IAM – are subject to uncertainty. Many of the parameters related to modelling dangerous climate change are subject to particular uncertainty. Yet CBA studies have not always chosen to tackle this uncertainty directly. The simplest modelling strategy in the literature is deterministic, whereby a 'best guess' is made for each parameter. This is still very common and would in many respects preclude the analysis of dangerous climate change, since the highest-damage scenarios plausible are far from the most likely.

Nevertheless most IAMs have also been set up at one time or another to run a Monte Carlo procedure, which makes repeated random draws of each parameter from its probability distribution. This enables climate impacts to be modelled probabilistically (e.g. Hope, 2006; Mastrandrea and Schneider, 2004; Plambeck *et al*., 1997; Roughgarden and Schneider, 1999). However, it is still somewhat limiting. First, the model structure remains deterministic. Second, the data from which IAM parameter distributions are calibrated often comprise different best guesses from underlying studies, rather than a full estimate of uncertainty within these studies. Thus probabilistic IAMs remain likely to underestimate overall uncertainty.

Moreover, very few of these studies extend to a proper application of expected-utility analysis (exceptions are Tol, 1999 and 2003), which enables a meaningful valuation of relative climate risks. An intermediate step is to generate a probability distribution of consumption, but then to calculate the (discounted) utility of mean consumption, in other words the utility of expected consumption. This is an incomplete application of the economics of risk of course (in the framework set out by von Neumann and Morgenstern, 1944), because we need to preserve information about the probability distribution of consumption in order to similarly value the probability distribution of social welfare.

What is required to support expected-utility analysis is the computation of discounted utility along each of the model's Monte Carlo draws. This is the core of the welfare valuation performed in the *Stern Review*. Begin by specifying the utility of the representative consumer as a simple, iso-elastic function of consumption per capita in the standard way:

$$u(t) = \frac{c(t)^{1-\eta}}{1-\eta} \tag{4}$$

Where u is utility per capita, c is consumption per capita and η is (the negative of) the elasticity of marginal utility with respect to consumption. There is an important wrinkle at this point, namely that η does up to three jobs. Positive η assumes the marginal utility of increments in consumption falls as initial consumption rises. Insofar as consumption is changing over time, it therefore becomes a measure of intertemporal inequality aversion (the elasticity of intertemporal substitution). Since consumption usually rises over time, it is usually a positive argument in the consumption discount rate (see below). In a regionally disaggregated model, it would similarly be a measure of inter-regional inequality aversion. And in a Monte Carlo model, it serves as a coefficient of (relative) risk aversion, quantifying the degree to which the representative consumer is averse to states of the world in which consumption is particularly low. So η captures the marginal valuation of climate costs over time, space and states of the world (Monte Carlo draws). This goes a long way to explain conflicts over what is the appropriate value of η (compare Dasgupta, 2006; Gollier, 2006; Nordhaus, 2006; and Quiggin, 2006).

Discounted per-capita utility is given by:

$$w = \int_{t=0}^{\infty} u(t) \exp^{-\delta t} \, dt \tag{5}$$

Where w is discounted utility per capita and δ is the pure rate of time preference or utility discount rate. Finally, with exogenous population, we would automatically weight by population to derive our aggregate social welfare or objective function:

$$W = \int_{0}^{\infty} N(t) u(t) \exp^{-\delta t} \, dt \tag{6}$$

Where W is social welfare and N is population. Every possible outcome i of climate change (i is a Monte Carlo draw), which has associated with it a probability p, should be evaluated with the social welfare function in equation (6). If we were also able to measure consumption and the impacts of climate change in different world-regions, then W should be calculated separately for each region. This is an item for further work. We are now able to compute expected utility for the probability distribution of consumption paths simulated to follow from a policy choice:

$$\mathrm{E}(W) = \sum_{i=0}^{N} p_i W_i \tag{7}$$

Where *E* denotes the expectation, for possible outcomes *i*=1,…,N. Thus we are discounting endogenously, and every possible consumption path will have a unique set of discount factors, and hence a unique average discount rate, associated with it. For any given Monte Carlo draw, the familiar Ramsey (1928) formula for the consumption discount rate is:

$$r_i(t) = \delta + \eta \frac{\dot{c}_i}{c_i}(t) \tag{8}$$

Where *r* is the consumption discount rate specific to Monte Carlo draw *i*. This is also an important point: some studies that do preserve the probability distribution of social welfare apply an exogenous discount rate (e.g. Hope, 2006). But this assumes growth in consumption that will not actually be realised by the Monte Carlo draw on which it operates (except by coincidence or where climate-change costs are on the whole minimal). The likely empirical consequence is an underestimate of the cost of climate change (Dietz *et al.*, 2006).

Tol (2003) notes that, for expected-utility analysis to be applicable, the costs of climate change must exhibit finite variance. His IAM, FUND, is specified to exhibit finite variance in its parameters (like PAGE), but convergence problems can nevertheless occur if consumption growth becomes persistently negative due to climate change. Discounting endogenously, the discount factors on one of his Monte Carlo draws become infinite.[7] The more general question is whether climate change can really be described as a situation of ‘risk’, in the sense that we know the full set of possible outcomes and their associated objective probabilities? In fact, many elements of the overall incertitude attached to the consequences of GHG emissions would better be described as situations of uncertainty, in the Knightian sense (Knight, 1921). That is, we do not know their objective probabilities. Whether CBA remains a meaningful decision-support tool then depends on our ability to define subjective probability distributions over the relevant variables. This is the necessary core of any stochastic modelling approach. If our ability to do so is very limited – or indeed if we are simply ‘ignorant’ of climate outcomes in the sense that we cannot even foresee what they will be, let alone how likely they are –

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[7] We cap impacts at 99% of GWP, in order to avoid this problem, which is quite likely in a damage function with a high exponent. Simply put, with high γ and save for very optimistic assumptions about adaptation, climate damage will inevitably exceed 100% of regional or global GWP if warming is allowed to increase sufficiently (e.g. to just under 6ºC above pre-industrial where γ=3, β=2 and there is no adaptation at all). Losses in GWP equal to, or in excess of, 100% stretch plausibility and should not in themselves cause us to abandon expected-utility analysis in favour of a specification that ignores uncertainty. In any case, with our analysis confined to the global level, this cap is highly unlikely to come into effect, except for one or two draws in the high-climate scenario (i.e. it rarely gets hot enough, even by the end of the modelling horizon in 2200). If the analysis is taken to the regional level, it may prove more important, as impacts in the poorest regions are additionally multiplied by a weight.

then so is the applicability of CBA.[8] Thus in presenting results for a baseline-climate scenario and a high-climate scenario – two discrete probability distributions – the *Stern Review* was quite explicit in pointing out that the relative likelihoods of the two distributions are unquantified. The decision problem is quite different in this case, essentially leading to an informal application of the precaution principle (Stern, 2006, p38-39).

3. Model description

The 2002 version of PAGE (hereafter PAGE2002) is comprehensively described in Hope (2006) and, unless otherwise stated, we make no changes to the parameters reported therein. The primary features of the model are as follows:

- Emissions of carbon dioxide and methane (including natural emissions stimulated by climate change in the model), as well as SF_6, and other GHGs that contribute to background radiative forcing (e.g. NO_2 and (H)CFCs);
- The accumulation of anthropogenic GHG emissions in the atmosphere and resulting radiative forcing;
- Regional temperature increases arising from the difference between greenhouse warming and regional cooling brought about by sulphate aerosols;
- Climate damage is a regional function of increases in regional mean temperature, as described in general-form in equation (1), but with the addition of adaptation (see below);
- Region-specific impacts of gradual climate change in two main sectors – (a) 'market' sectors of the economy like agriculture and energy and (b) direct welfare impacts on ecosystems and human health ('non-market' sectors). With respect to equation (1), each sector has a unique probability distribution for β but the distribution for γ is common to both;
- Adaptation, which requires costly investment, increases a time-varying tolerable level of climate change before damage to market sectors arises and reduces the intensity of impacts on both market and non-market sectors above the tolerable level;
- The possibility of a future macro-discontinuity, as per equation (2).

31 key inputs to the model are stochastic and we take 1000 Monte Carlo draws. The density functions for the various parameters are calibrated on the underlying scientific and economic literatures on

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[8] Broader social-scientific perspectives on uncertainty also point to 'ambiguity' or 'fuzziness' (e.g. Stirling, 1998), in the sense that the probabilities of different climate outcomes might be known (at least subjectively in terms of temperature, sea-level, precipitation and so on), but the consequences of these outcomes can be interpreted in different ways (i.e. how do we weigh up economic, social and ecological impacts?). CBA of course finesses this element of incertitude by imposing a particular value framework.

climate change. Thus PAGE2002 is essentially meta-analytical and has in the past been shown to produce results, for instance with respect to the marginal damage cost of carbon (calculated without full expected-utility analysis), close to the centre of a range of peer-reviewed studies (cf. Hope, 2006 with Tol, 2005). Assumptions particular to the *Stern Review* and this paper are reported in table 1.

TABLE 1 HERE

4. Results

We begin with a brief summary of the undiscounted cost of climate change through time (figures 2 and 3), starting in 2050. Figure 2 traces the mean percentage loss in GWP, as well as the range of losses from the 5th to the 95th percentile, for the baseline-climate scenario. Figure 3 does the same for the high-climate scenario.

FIGURES 2 AND 3 HERE

The cost of BAU climate change in figures 2 and 3 is the sum of climate-change impacts and adaptation costs, but in practice the latter are very small in comparison. Thus the figures trace the global damage costs of climate change simulated by PAGE2002. Two key features become apparent. The first is that the greater portion of undiscounted damages fall in the second half of the modelling horizon, between 2100 and 2200. In the baseline-climate scenario, mean damages are 2.6% of GWP in 2100, but 11.3% in 2200. In the high-climate scenario, they are 2.9% in 2100 and 13.8% in 2200. This is due to the convexity assumed in the damage functions, as well as the increased risk of a macro-discontinuity with direct impacts, neither of which has a strong effect until regional temperatures are sufficiently high, mostly after 2100 (higher of course in the high-climate scenario, due to the positive natural GHG feedback). The second is uncertainty around the mean estimates. The 5-95% confidence interval becomes increasingly wide as time passes and by 2200 it spans a range from 2.9% to 29.4% of GWP in the baseline-climate scenario and from 2.9% to 35.2% of GWP in the high-climate scenario.

Figures 2 and 3 present the dynamic costs of climate change relative to consumption growth in a world without climate change. The socio-economic scenario used by the *Review* (table 1) puts that growth at an average of 1.3% per capita per annum over the period 2001-2200. Global average per-capita consumption rises from around $6000 in 2001 to $79000 in 2200. This trend growth is far in excess of the damage caused by climate change, so that, even under the 95th percentile damages in the high-climate scenario, consumption is higher in 2200 than it is now (c. $41000). Furthermore, even under these damages, consumption growth is positive over the whole modelling horizon.

Preliminaries aside, we now test the sensitivity of the *Stern Review's* estimates to two key elements of the welfare valuation of climate damages: the elasticity of marginal utility of consumption η and the pure rate of time preference or utility discount rate δ. Thus we briefly put the forthcoming results in context, by establishing how sensitive estimates are to discounting. But due to the dual role of η, we also gain some sense of the importance of risk aversion compared with intertemporal inequality aversion.

Tables 2 and 3 investigate the sensitivity of the total cost of BAU climate change to increases in η and δ for the *Review's* baseline-climate and high-climate scenarios. The total cost of climate change is derived from a comparison of the 'balanced growth equivalent' or BGE of consumption without climate change to the BGE of consumption after climate damage and adaptation costs have been deducted (Stern, 2006, p183). The BGE difference summarises modelled losses over time, regions of the world and possible states of the world in terms of a one-off, permanent loss of global mean per-capita consumption today.

We test values of δ in the range 0.1% to 1.5% per annum. 0.1% is the value taken in the *Review* and follows from a 'prescriptive' approach. 1.5% per annum corresponds to a relatively rigorous, 'descriptive' estimate of the pure rate of time preference that would follow from the preferences of those currently alive (Pearce and Ulph, 1999). For η, we take 1 to 3. The *Review* applied a value of 1 (giving the special case log utility function), which is quite well supported by some recent empirical evidence (Cowell and Gardiner, 1999; Pearce and Ulph, 1999). However, the combination of δ=0.1% with η=1 does place a lot of weight on impacts in the far-off future. This is of particular concern, since the *Review's* BGE method extrapolates the percentage of consumption lost due to climate change in 2200 on to infinity. As a result, the share of total discounted utility over all time falling after 2200, beyond the PAGE modelling horizon, is large when η=1 and δ=0.1%.

TABLES 2 AND 3 HERE

Comparing both tables, we can see that increases in the pure time discount rate significantly reduce estimates of the total cost of climate change, as critiques of the *Review* have noted (esp. Nordhaus, 2006). Increasing δ reduces the importance of future climate-change costs in present-day decisions. In the baseline-climate scenario, for example, increasing δ from 0.1% p.a. to 1.5% p.a. reduces the mean total cost of BAU climate change from 11.1% to 3.3%, where η is 1. In the equivalent column for the high-climate scenario, the mean estimate falls from 14.7% to 4.2%.

Increasing η has more complex effects, because it increases both the rate of intertemporal inequality aversion (in effect it increases the consumption discount rate) and risk aversion. The former is true, because we saw above that consumption is always increasing through time, so increases in η only serve to increase the consumption discount rate (if consumption growth were locally negative, an increase in η would reduce the consumption discount rate). In the baseline-climate scenario, increasing η from 1 to 3 reduces the mean total cost of BAU climate change from 11.1% to 1.3%, where δ is 0.1% p.a. In the high-climate scenario, initial increases in η from 1 to 2 reduce the mean total cost of climate change (from 14.7% to 7.4% where δ is 0.1% p.a.). But further increases in η from 2 to 3 actually drive the equivalent estimates back upwards again, from 7.4% to 13.2%. This means that, while in most instances increases in η have a greater positive effect on intertemporal inequality aversion than they do on risk aversion, the opposite is true when upper-bound values of η are applied to the high-climate scenario. This is intuitive, since the high-climate scenario realises the highest global temperatures, which work through to produce the highest damage and the lowest consumption. We are assumed to be highly averse to scenarios that produce very low consumption when η lies in the range 2.5-3. Compare the mean total cost of climate change with the corresponding 5-95% confidence interval. When η lies in the range 2.5-3, the mean lies below even the 95th percentile, because consumption is very low in scenarios that are less than 5% likely, and this feeds through to extremely low utility. Such a result is important, because it illustrates that arguments cast in terms of 'the' discount rate may be mistaken. In particular, following expected-utility analysis, it shows that the effect of an increase in η is *a priori* ambiguous and does not always simply work to reduce the present-value of climate damage.

In section two, we speculated that insufficient treatment of uncertainty could cause misleading results. We can test this proposition on the *Review* estimates by using PAGE2002 to simulate a range of modelling strategies, each of which takes risk into account to a different degree. Table 4 presents estimates from four modelling approaches.

1. **'All modes'.** The first is to set all stochastic parameters in PAGE2002 to their mode values. This simulates a modelling strategy in which best guesses are made about the value of all parameters, 'best' in the sense of being most likely.
2. **'All means'.** The second is to set all stochastic parameters in PAGE2002 to their mean values. This also simulates a deterministic strategy, but the mean of the joint probability distribution of climate-change costs will differ from the mode, if the distribution is asymmetric. Indeed, it is

generally acknowledged to have a ‘fat left tail’ of severe impacts with a low probability, so the mean cost should be higher.

3. **‘Expected consumption’.** The third utilises the standard stochastic specification of PAGE2002, but instead of carrying out full expected-utility analysis, we calculate the utility of expected consumption.
4. **‘Expected utility’.** The fourth solves for the BGE equivalent to the expected utility of consumption.

TABLE 4 HERE

From table 4 it is clear that a modelling strategy based on taking mode values for all parameters – equivalent to a best-guess strategy – leads to a significant underestimate of the total discounted cost of climate change, relative to an expected-utility approach. In the baseline-climate scenario, this strategy yields an estimate of the BGE loss that is 3.5% of present global mean consumption per capita, relative to a mean of 11.1% when expected-utility analysis is applied. In the high-climate scenario, the ‘all modes’ strategy performs even worse, estimating a 4.6% BGE loss, compared to 14.7% using expected-utility analysis. Moving to an ‘all means’ strategy reduces the shortfall significantly, although it is still 3.1 percentage points below at 8% in the baseline-climate scenario. Similarly, it is 3.7 percentage points below at 11% in the high-climate scenario.

Calculating the utility of expected consumption brings the estimates much closer. In the baseline-climate scenario, it is 10.4%, which is just 0.7 percentage points below the expected-utility estimate. However, the expected-consumption strategy does perform worse in the high-climate scenario, falling short by 2 percentage points. As before, the higher temperatures estimated by the high-climate scenario produce a slightly higher likelihood of scenarios in which the impacts of climate change are very severe indeed. Even with relatively modest risk aversion (recall that here η=1), the need to value these risks systematically is clear.

This last point indicates that the analysis can be usefully extended to consider how the expected-consumption strategy performs relative to the expected-utility strategy for higher values of η. This enables further investigation of how the estimation of dangerous climate change, by our definition, is affected by modelling impacts on consumption on the one hand, and valuing consumption in utility terms on the other. Table 5 presents the analysis for η=1, 2 and 3. In the baseline-climate scenario, increases in η reduce the absolute shortfall between the expected-consumption estimate and the expected-utility estimate, from 0.7 percentage points where η is 1 to 0.2 percentage points where η is 3.

However, the relative shortfall is in fact rising, from 6.3% as a share of the expected-utility estimate where η is 1, to 15.4% where η is 3. This result is much magnified in the high-climate scenario. When η is 1, the shortfall caused by taking an expected-consumption approach is 2 percentage points or 13.6%. But when η is 3, the shortfall is 11.9 percentage points, or 90.2% of the expected-utility estimate. If we do believe that this is the appropriate consumption elasticity of utility in a simple framework, then the last result demonstrates that even an expected-consumption approach, which at least rests on stochastic modelling, understates the risks we face, possibly by a large amount. It also demonstrates the role of welfare valuation in the overall monetisation of dangerous climate change.

TABLE 5 HERE

To summarise at this stage, tables 4 and 5 demonstrate the proposition that insufficient treatment of uncertainty leads to estimates of the cost of BAU climate change that are misleadingly small. Similar results have been produced by past studies, although they have not focused on the issue in such detail.[9] Furthermore, the difference between a comprehensive, expected-utility approach and simpler approaches is often large. Broadly, the differences revealed are of the same magnitude as those produced by different assumptions about discounting. Moving from an ‘all modes’ modelling strategy to expected-utility analysis increases the mean total cost of BAU climate change by 7.6 percentage points in the baseline-climate scenario. Increasing the pure rate of time preference from 0.1% p.a. to 1.5% p.a. produces a 7.8 percentage point rise in that same scenario.

Recent scientific evidence increases the imperative to adopt an expected-utility approach, since it has raised the possibility of very large impacts and as a result has effectively increased the confidence interval around the future consequences of climate change. The bigger differences between modelling strategies in the high-climate scenario reflect this, insofar as the high-climate scenario takes on board the possibility of dangerous positive natural feedbacks in the warming process.

We now examine sensitivity to the damage function exponent γ. In addition, we analyse how uncertainty about the damage function exponent interacts with different degrees of risk aversion. This is likely to be an important interaction, since higher values of γ – more convexity in the damage function – increase the likelihood of very severe impacts. The discussion above demonstrates the significance of the welfare valuation of such risks. That is, dangerous climate change in a welfare-economic sense is as much about the welfare valuation of impacts as it is about their initial estimation.

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[9] e.g. Azar and Lindgren (2003), Tol (1999).

In table 6, we treat γ as deterministic and estimate BGE losses for a range from 1 to 3, at the same time examining how that range interacts with a range of η – the elasticity of marginal utility of consumption, describing inequality and risk aversion – from 1 to 3. The analysis is confined to the baseline-climate scenario and holds δ constant at 0.1% p.a.

TABLE 6 HERE

Where the consumption elasticity of marginal utility, η, equals 1, increasing γ from 1 to 2 raises the mean total cost of climate change from 5.4% of present global mean consumption per capita to 10.4%, an increase of 92% in relative terms. A power of 2 produces an estimate closest to the *Stern Review's* main result, reported in table 2. Thus where η=1, our summary estimate of the total cost of climate change is indeed very sensitive to the damage function exponent, as the Postscript to the *Review* also suggested. However, where η=3, the mean total cost of climate change increases from 0.9% to just 1.1% for γ=2, a rise of just 0.2 percentage points or around 22% in relative terms. We would indeed have expected all estimates to fall, since raising the consumption elasticity of marginal utility increases intertemporal inequality aversion and thus the consumption discount rate under rising consumption. But the relative effect of changes in the damage function exponent has also fallen. This indicates that increases in η work to a greater extent to increase intertemporal inequality aversion than they do to increase risk aversion, for this relatively modest range of damage function exponents.

However, increasing γ beyond 2 paints a different picture for our overall evaluation. The mean total cost of climate change increases to 33.3% where γ=3 and η=1. Moreover, as risk aversion increases, the range of estimates increases too. Where η=3, the total cost estimate jumps to 51.9%, as γ increases to 3. Comparing the mean cost with the 90% confidence interval shows that, where γ=3 and η=3, the mean lies far beyond the 95th percentile estimate. So if we ascribe high values to η, perhaps based on empirical evidence on risk aversion, then assumptions about the convexity of damage become all the more important. A very few Monte Carlo draws are driving the welfare valuation in this case, because we are deemed to be highly averse to running the risk of these outcomes being realised.

We move on in table 7 to investigate sensitivity to the PAGE model's third pathway to 'dangerous' climate change, the risk of a macro-discontinuity with direct economic impacts. We treat each of the three parameters in equation (3) as deterministic and estimate BGE losses for their minimum, mode and maximum values, once again in interaction with different assumptions about η. To recap, the three parameters are ζ, the loss in GDP if a macro-discontinuity occurs (minimum 5%, mode 10%, maximum 20%), θ, the probability of a macro-discontinuity (minimum 1 percentage point per °C rise in global mean temperature, mode 10 ppts., maximum 20 ppts.), and $T_{TRIGGER}$, the threshold global mean temperature, above which a macro-discontinuity becomes possible (minimum 2ºC, mode 5ºC, maximum 8ºC). The analysis is for the baseline-climate scenario, with δ=0.1% p.a. and γ stochastic.

TABLE 7 HERE

Table 7 demonstrates that cost estimates are also sensitive to variations in the three parameters, which jointly determine the risk of a macro-discontinuity with direct impacts. Looking first at ζ, the loss in GDP if a macro-discontinuity occurs, increasing that loss from 5% to 20% increases the present value of the mean total cost of climate change from 7.9% to 12.9%, in our central case where η=1. If we now examine the results of interacting increases in ζ with increases in η, we see an interesting 'tipping point' of the kind identified in table 3 and in examining the sensitivity of estimates to very high values of γ. Where ζ is in the range 5% to 10%, increases in η from 1 to 3 straightforwardly reduce the mean total cost of climate change. As before, the reason is that intertemporal inequality aversion dominates risk aversion. However, when ζ is 20% and η is 3, the mean total cost estimate rebounds markedly, to 39.5%. As before, comparing the mean to the 90% confidence interval indicates that a very small share of Monte Carlo draws, less than 5% likely, must drive this result. Estimates are similarly sensitive to variations in θ and $T_{TRIGGER}$, but with the important difference that there is no such tipping point in these cases.

Finally, we return to the issue of utility or pure time discounting, because much of the preceding analysis has been based on near-zero time preference (δ=0.1% p.a.). In table 8, we briefly recapitulate the previous sensitivity analysis with a utility discount rate of 1.5% per annum. We do so by reanalysing the maximum differences in our estimates of the mean total cost of climate change from tables 4, 6 and 7. Thus we first present the difference in BGE losses under the high-climate scenario for an 'all modes' modelling strategy, compared with expected-utility analysis, where η=1. This illuminates the effect of modelling and valuing uncertainty under higher pure time discounting. Second, we present the difference in BGE losses between damage function exponents, γ, of 1 and 3, where η=3. Finally, we present the differences brought about by losses in GDP if a macro-discontinuity occurs, ζ, of 5% and 20%, again where η=3.

TABLE 8 HERE

As we would expect, BGE losses are in all cases lower than their equivalents in tables 4, 6 and 7, because an increase in the utility discount rate reduces the present value of climate damages and adaptation costs falling in the future, especially in the medium and long run. Similarly, the differences between the estimates are smaller in absolute terms. Thus moving from a modelling strategy based on taking mode values for all parameters to a strategy based on expected-utility analysis increases the mean total cost of climate change by just 2.8 percentage points, from 1.4% to 4.2%. This compares with an equivalent 10.1 percentage point increase where δ=0.1% p.a., from 4.6% to 14.7% (see table 4). Similarly, increasing γ from 1 to 3 brings about an absolute increase in the BGE loss of 12.7 percentage points, from 0.4% to 13.1%. This compares to an equivalent increase of 51 percentage points where δ=0.1% p.a., from 0.9% to 51.9% (table 6). And increasing ζ from 5% of GDP to 20% of GDP results in an absolute increase in the BGE loss of 7.3 percentage points, from 0.5% to 7.8%. Compare this with a 38.5 percentage point increase where δ=0.1% p.a., from 1.0% to 39.5% (table 7).

While in the case of modelling strategies the relative differences are very similar (around a 200% increase on the lower estimate), in terms of γ and ζ they are much reduced by raising the utility discount rate. As γ rises from 1 to 3, the BGE loss increases by over 3000% relative to the estimate where γ=1. While evidently an enormous relative change, brought about by high aversion (η=3) to the small risk of severe climate impacts (less than 5% of Monte Carlo draws), the equivalent relative change calculable from table 6 is around 5700%. The explanation lies in the relationship between time and the convexity of climate-change impacts. The Monte Carlo draws that drive these welfare estimates where η is 3 do not deliver their severe impacts until after 2100, by which time higher utility discounting has muted their effect on welfare valuation. Much the same is true of an increase in ζ, where the relative differences are around 1500% and 4000% relative to the lower estimate respectively. Nevertheless, in closing it is worth emphasising that, in the extreme high cases reported in table 8, the present value of the total cost of climate change is still large in absolute terms, even with a higher utility discount rate. While it is beyond the scope of this paper to perform optimisation, it is fairly safe to say that a present-value cost of 13.1% (where η=3 and γ=3) is large enough to warrant stabilisation of atmospheric GHG concentrations at a low level.

5. Discussion

By some accounts, the overriding reason why the *Stern Review* estimates of climate damage are high is a low discount rate (e.g. Dasgupta, 2006; Nordhaus, 2006). This is certainly true to some extent, because a high utility discount rate – one component of the consumption discount rate – renders the present value of climate damage in the far-off future so low that it becomes almost always largely irrelevant how big that damage is. But if we accept a low utility discount rate, then present-value estimates become heavily dependent on how risk and uncertainty are taken into account and valued, allied to assumptions about the likelihood of dangerous climate change. The *Stern Review's* IAM and welfare valuation includes a wide range of risks and values them systematically on the basis of expected-utility analysis. It also includes three pathways through which dangerous climate change, in the sense of rapid and large-scale losses in global consumption, can materialise. First, it allows for rapidly escalating costs of gradual climate change in its specification of the damage function exponent. Second, it allows for abrupt, large-scale and discontinuous positive natural feedbacks in the climate system through its high-climate scenario. Third, it includes a fairly novel but speculative function for the direct impacts of abrupt, large-scale and discontinuous climatic changes. We have argued that an IAM, which includes the possibility of dangerous climate change, is consistent – if not in a strict sense – with an approach that assumes some natural capital is 'critical'.

We have set out how the *Stern Review* incorporates the economics of risk and demonstrated that doing so makes a big difference to damage estimates. But climate change is at best a problem characterised by Knightian uncertainty. That is to say, modellers are essentially undertaking a monumental exercise in assigning subjective probabilities – in Bayesian decision theory. At worst, climate change would better be characterised as a problem of ignorance. For example, IAMs currently make no explicit estimates of the damages resulting from 'socially contingent' impacts (Downing *et al*., 2005). Thus IAMs are ignorant of these scenarios. Similarly, warming in the *Review's* high-climate scenario still lies well within the extremes reported in Meinshausen's (2006) synthesis of eleven studies. In fact, the *Review* touched briefly on the problems that arise when one cannot define a continuous probability distribution over all outcomes. This is evident in the conundrum of how to weigh up the consequences of the *Review's* baseline- and high-climate scenarios, because we have no quantification of their relative likelihoods. Thus the *Review* relies on an informal, qualitative application of precaution. Then there is the question of ambiguity or fuzziness in the interpretation of probabilities (e.g. Stirling, 1998): the notion that, even if we could constrain our estimates of the consequences of climate change in terms of, say, global mean temperature, it is not clear how to interpret these consequences, because weighing up economic, social and environmental impacts is a question of value. CBA makes a particular value judgement and naturally there are rival ethical approaches, such as those based on rights, that are given extremely short thrift in the process. Thus, for all these reasons, a broad range of evidence is required to support recommendations on climate-change mitigation. Ironically, the *Stern Review* was acutely aware of this (Stern, 2006, chapter 2). To a large extent, critics of the *Review* miss the point that arguments for stabilisation were based first and foremost on a disaggregated analysis of climate impacts (chapters 3-5).

So what is the worth of formal economic modelling? It certainly does not lie in providing precise estimates of climate damage and a precise optimal pathway for GHG emission reductions. This is most especially true of CBA studies that altogether avoid including impacts, about which measurement and valuation is currently most difficult and uncertain (esp. Mendelsohn *et al*., e.g. 1999). Rather it lies in obtaining an order-of-magnitude quantification of the economic consequences of unabated climate change. And it certainly helps to make the consequences of key value judgements on time preference and risk and inequality aversion systematically clear. δ and η are not just economic technicalities, as some have insinuated. All approaches make implicit judgements embodied in these parameters. It is to the great credit of the CBA approach that such assumptions are made explicit and their consequences tested rigorously. As such we could think of IAMs as a canvas on which debates about intergenerational fairness, the distribution of wealth, and the management of risk and uncertainty, are 'painted'.

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Figure 1. Impacts of gradual climate change and their sensitivity to the damage function exponent.

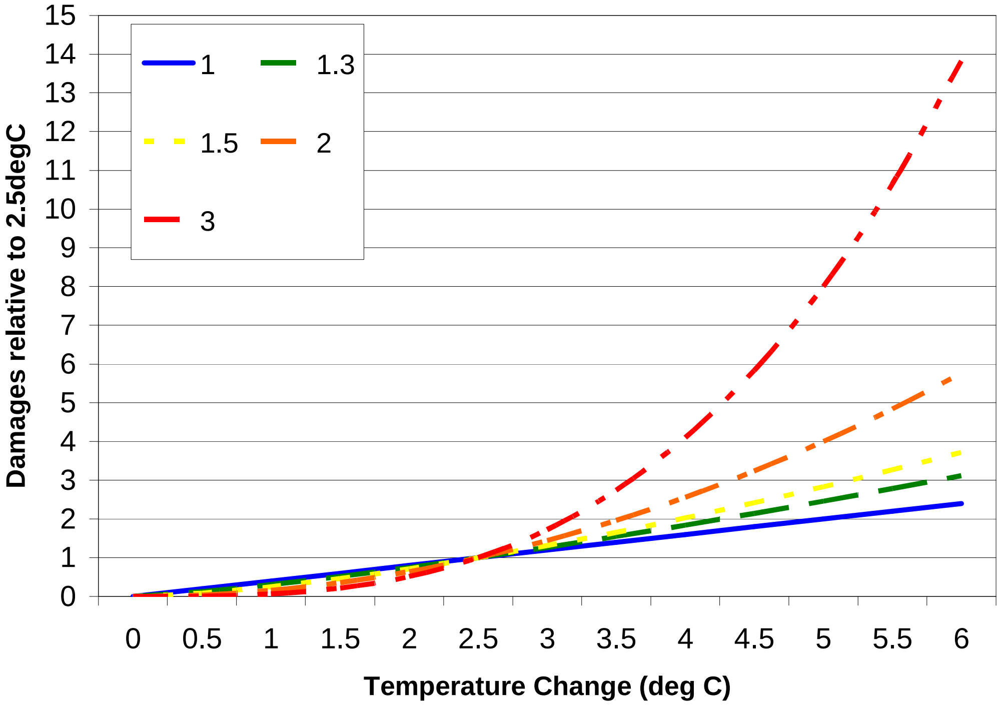

Figure 2. Dynamic costs of climate change in the baseline-climate scenario.

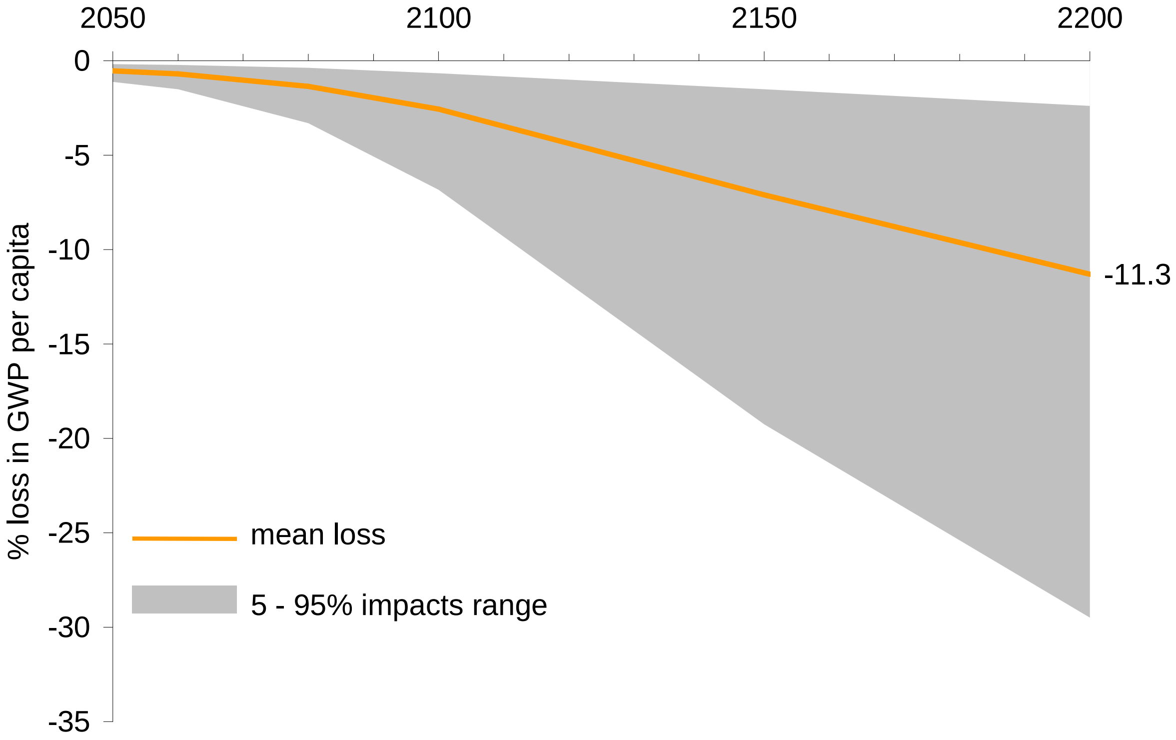

Figure 3. Dynamic costs of climate change in the high-climate scenario.

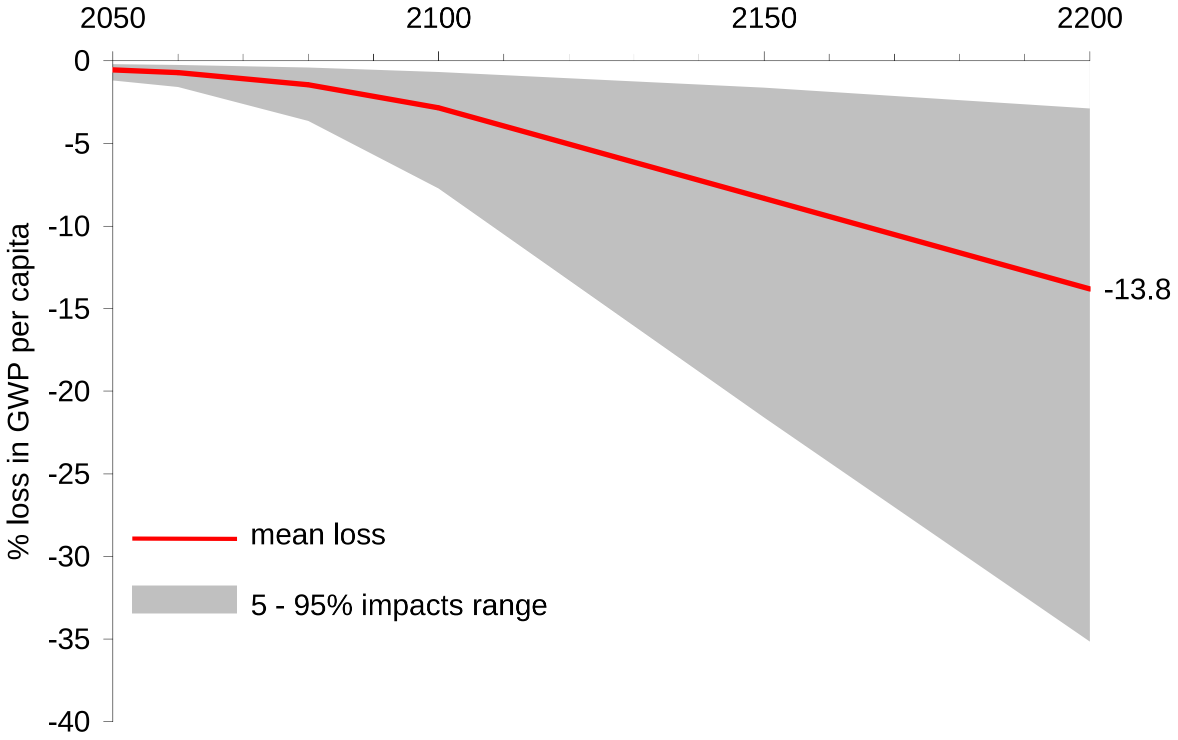

Table 1. Summary of assumptions.

Parameter	*Assumption*
Economic growth	Based on IPCC A2 scenario (see Nakicenovic and Swart, 2000), converted to PPP and extrapolated to 2200 in Hope (2006).
Population growth	As above
Saving rate	0.2, constant
Constant rate of growth of consumption per capita after 2200	1.3% p.a. (the average between 2001 and 2200 without climate change)
Climate sensitivity	Triangular probability density function <1.5, 2.5, 4.5> (ºC)

Table 2. Sensitivity of total cost of climate change to pure rate of time preference and consumption elasticity of marginal utility in baseline-climate scenario (mean BGE loss, 5-95% confidence interval). *Stern Review* estimate in bold.[10]

Pure rate of time preference (δ)	*Consumption elasticity of marginal utility (η)*				
	1.0	*1.5*	*2.0*	*2.5*	*3.0*
0.1	**11.1** **(2.4-27.7)**	6.5 (1.7-16.5)	3.6 (1.1-9.4)	2.1 (0.6-5.5)	1.3 (1.8-4.6)
0.5	8.1 (1.7-20.4)	4.5 (1.2-11.7)	2.6 (0.8-6.7)	1.5 (0.6-4.0)	1.0 (0.4-2.4)
1.0	5.2 (1.2-13.2)	2.9 (0.8-7.5)	1.6 (0.5-4.3)	1.1 (0.5-2.6)	0.7 (0.3-1.6)
1.5	3.3 (0.7-8.5)	1.9 (0.6-4.9)	1.1 (0.4-2.9)	0.8 (0.4-1.8)	0.7 (0.3-1.3)

Table 3. Sensitivity of total cost of climate change to pure rate of time preference and consumption elasticity of marginal utility in high-climate scenario (mean BGE loss, 5-95% confidence interval). *Stern Review* estimate in bold.

Pure rate of time preference (δ)	*Consumption elasticity of marginal utility (η)*				
	1.0	*1.5*	*2.0*	*2.5*	*3.0*
0.1	**14.7** **(2.7-33.0)**	10.2 (2.0-20)	7.4 (1.1-12.2)	8.1 (0.7-6.9)	13.2 (1.8-5.3)
0.5	10.6 (2.0-24.4)	6.5 (1.4-15.2)	4.7 (0.9-8.5)	5.0 (0.6-4.9)	7.8 (0.5-2.9)
1.0	6.7 (1.3-16.0)	4.0 (1.0-9.6)	2.7 (0.5-5.4)	2.7 (0.5-3.1)	3.9 (0.3-1.9)
1.5	4.2 (0.8-10.1)	2.5 (0.7-6.0)	1.7 (0.5-3.4)	1.6 (0.4-2.2)	2.1 (0.3-1.4)

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[10] The small discrepancy is attributable to different sets of 1000 Monte Carlo draws.

Table 4. Estimates of the total discounted cost of BAU climate change under different modelling strategies (δ=0.1% p.a., η=1.0). ***Stern Review*** **estimate in bold.**

Modelling strategy	*Baseline climate (% BGE loss)*	*High climate (% BGE loss)*
All modes	3.5	4.6
All means	8.0	11.0
Expected consumption	10.4	12.7
Expected utility (mean loss)	**11.1**	**14.7**

Table 5. Comparing expected-consumption and expected-utility approaches with different degrees of risk aversion. *Stern Review* estimate in bold.

Climate scenario	*Modelling strategy*	*Elasticity of marginal utility of consumption (η)*		
		1.0	*2.0*	*3.0*
Baseline	*Expected consumption*	10.4	3.3	1.1
	Expected utility (mean loss)	**11.1**	3.6	1.3
High	*Expected consumption*	12.7	4.0	1.3
	Expected utility (mean loss)	**14.7**	9.2	13.2

Table 6. Variations in the total discounted cost of BAU climate change with the damage function exponent and the consumption elasticity of marginal utility (baseline-climate scenario, δ=0.1% p.a.).

Damage function exponent (γ)	*Consumption elasticity of marginal utility (η)*		
	1	*2*	*3*
1	5.4 (1.3-12.1)	1.9 (0.8-4.3)	0.9 (0.4-1.7)
1.5	7.2 (1.7-16.6)	2.4 (0.9-5.7)	1.0 (0.4-2.1)
2	10.4 (2.2-22.8)	3.3 (0.9-7.8)	1.1 (0.4-2.7)
2.5	16.5 (3.2-37.8)	5.2 (1.1-13.2)	1.6 (0.5-4.3)
3	33.3 (4.5-73.0)	29.1 (1.7-35.1)	51.9 (0.5-13.8)

Table 7. Variations in the total discounted cost of BAU climate change with the probability and direct impacts of a macro-discontinuity and the consumption elasticity of marginal utility (baseline-climate scenario, δ=0.1% p.a.).

		Consumption elasticity of marginal utility (η)		
		1	*2*	*3*
ζ (% GDP)	*5*	7.9 (1.8-20.6)	2.6 (0.9-6.7)	1.0 (0.4-2.3)
	10	9.5 (1.9-22.1)	3.4 (0.9-7.4)	1.7 (0.4-2.6)
	20	12.9 (2.1-29.2)	8.3 (0.9-10.4)	39.5 (0.4-3.5)
θ (ppts. per ºC)	*1*	6.6 (1.6-17.8)	2.3 (0.8-5.6)	1.0 (0.4-1.9)
	10	9.5 (1.9-22.3)	3.1 (0.9-7.6)	1.2 (0.4-2.7)
	20	12.8 (2.0-31.8)	4.2 (0.9-10.8)	1.4 (0.4-3.5)
$T_{TRIGGER}$ *(ºC)*	*8*	7.3 (1.5-18.9)	2.6 (0.8-6.2)	1.1 (0.4-2.2)
	5	9.6 (1.7-23.7)	3.0 (0.9-7.8)	1.0 (0.4-2.5)
	2	13.6 (4.1-27.4)	4.9 (1.7-10.5)	1.9 (0.6-4.2)

Table 8. Further sensitivity of the total discounted cost of climate change, with a higher pure rate of time preference (δ=1.5% p.a.).

Variation	*Consumption elasticity of marginal utility (η)*	*Low estimate*	*High estimate*
Modelling strategy: *'All modes' to 'expected utility'*	*1*	1.4	4.2
Damage function exponent, γ: *1 to 3*	*3*	0.4 (0.3-0.9)	13.1 (0.2-2.8)
Loss of GDP if macro-discontinuity occurs, ζ: *5% to 20%*	*3*	0.5 (0.2-0.9)	7.8 (0.3-1.2)