Discounting and the social cost of carbon: a closer look at uncertainty

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ABSTRACT

Recently, in the economics literature, several papers have put forward arguments for using a declining discount rate in social-cost benefit analysis. This paper examines the impact of employing a declining discount rate on the social cost of carbon—the marginal social damage from a ton of emitted carbon. Six declining discounting schemes are implemented in the FUND 2.8 integrated assessment model, including the recent amendments to the Green Book of HM Treasury (Treasury, H.M., 2003. The Greenbook: Appraisal and Evaluation in Central Government. TSO, London). We find that using a declining schedule of discount rates increases the social cost of carbon estimate by as little as 10% or by as much as a factor of 40, depending upon the scenario selected. Although the range of plausible estimates is large, using declining discounting schemes in FUND 2.8 in most cases does not yield values at the £70/tC level suggested by UK DEFRA [Clarkson, R., Deyes, K., 2002. Estimating the social cost of carbon emissions. Government Economic Service Working Paper. HM Treasury, London]. Indeed, only at the higher end of the values of social cost of carbon found here would many climate change related policies – such as the Kyoto Protocol – pass a cost-benefit analysis. This conclusion, however, does not necessarily undermine the ethical and political economic reasons for supporting international collective action on climate change.

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1. Introduction

Comparisons of costs and benefits play a significant role in climate change policy. Results from cost-benefit analysis have been a major reason behind the refusal of the United States to ratify the Kyoto Protocol (Pearce, 2003). Similar calculations can explain the large side payment demanded by Russia for signing the Protocol. The widely publicised 'Copenhagen Consensus' used a cost-benefit analysis framework to examine solutions to 10 pressing global problems, including climate change, and subsequently promoted the (arguably misleading) headline conclusion that climate control is a 'bad' global investment (Lomborg, 2004; Sachs, 2004).

Given the importance of cost-benefits analysis, it is crucial to understand the framework and assumptions being employed behind such calculations. The headline conclusion promoted by Lomborg (2004) obscured the fact that the three authors of the papers on climate change – Cline (2004),

Manne (2004) and Mendelsohn (2004) – support a degree of early action to limit carbon emissions. Where the authors did disagree, such as on the optimal pathway to curb greenhouse gases, their differences of opinion were driven by different assumptions, especially concerning the appropriate discount rate.

This paper considers the impact of different discount rate frameworks on estimates of the social cost of carbon (SCC), a critical element in the cost-benefit analysis of climate change. The SCC is a monetary indicator of the global damage done by the emission of one extra ton of carbon today. In cost-benefit analysis of projects to control greenhouse gas emissions, the SCC is employed to measure the financial value of the damages avoided, and therefore the benefit of the mitigation project. The larger the SCC, the more attractive is investment in greenhouse gas emissions reductions.

Two reasons in particular provide justification for research into improving SCC estimates. First, the SCC is needed in order to find the economically optimal level of pollution control. Like many forms of environmental pollution, the optimal level of greenhouse gas pollution is not zero, for the simple reason that reducing such pollution is expensive. Without a measure of the damages avoided by pollution control, determining the optimal quantity is impossible. Second, explicit use of SCC reduces policy inconsistencies. As Thomas (1963) noted, ''the setting of any quality criterion or standard relating to health and wellbeing inevitably entails making an implicit estimate of cost/benefit ratios based on whatever data or other factors available.'' In the case of climate change, any mitigation measure inevitably involves a particular shadow price of carbon, whether stated implicitly or explicitly. A reliable estimate of the social cost of carbon provides government with an explicit shadow price of carbon that helps to minimise policy inconsistencies. This motivation is not invalidated by the fact that any estimate of the SCC will, invariably, reflect many uncertainties. Acting on a relatively plausible estimate is arguably better than no estimate at all (Hanemann, 1994; cf. Diamond and Hasuman, 1994). Some form of comparison of costs and benefits – implicit or explicit – is ultimately unavoidable (Pearce, 2003).

The SCC is generally estimated by employing an integrated assessment model, which combines a scientific model of global warming with a socio-economic model of the underlying value of the impacts. In these models, impacts at different times in the future are estimated and discounted back to present values to find the damage of a marginal ton emitted into the atmosphere. The choice of discount rates and discounting schemes therefore has a significant influence on the final estimate. Differences in the discounting schemes assumed by different modellers are one of the major drivers of variability in the estimates of the SCC (Tol, 2005). Traditionally, constant discount rates have been employed, although some recent economic literature suggests that a time varying, particularly a declining discount rate is more suitable for long-term problems such as climate change (Groom et al., 2005). Based upon some relatively rough calculations, Pearce et al. (2003) conjecture that shifting from a flat social discount rate of 4% to the declining discount rate proposed by Weitzman (2001) would roughly double the estimate of the social cost of carbon.

This paper tests that conjecture by employing a more sophisticated sensitivity analysis on declining discounting schemes in FUND (Climate Framework for Uncertainty, Negotiation and Distribution), one of the leading integrated assessment models. Our analysis is not concerned with determining the 'correct' value of the SCC. Neither do we propose that the discount rates used in CBA should decline in a particular way, or indeed that they should necessarily decline in all situations. We are interested instead in the comparative effects of shifting from a flat to a declining social discount rate scheme on both the mean and the range of estimates for the SCC. In other words, we aim to provide more information about the implications of using declining discount rates for climate change economics and policy.

The paper proceeds as follows. The first two sections provide theoretical background—Section 2 reviews past estimates of the SCC and Section 3 examines the recent advances in the theory of social discounting. Section 4 presents our methodology, including an overview of the FUND 2.8 model. Section 5 presents the results of the analysis, and Section 6 discusses the policy implications. Section 7 concludes.

2.   The social cost of carbon

In 1996, the IPCC Working Group III published a review on the first generation models (Pearce et al., 1996). The range of estimates reported by the review was $5–$125/t of carbon (in 1990 prices, or $6–$160/tC in 2000 prices). It was also estimated that this range was to increase to $7–$154/tC (in 1990 prices) for the period 2001–2010 (because the marginal damage of carbon tends to increase with the level of atmospheric concentration of CO_2).

In 2002, the UK Government Economic Service (GES) and Department for Environment, Food and Rural Affairs (DEFRA) published a review based on nine major studies (Clarkson and Deyes, 2002). The recommended SCC was approximately £70/tC ($105/tC)[1] in 2000 prices with equity weighting, with a range of £35–£140/tC ($52–$210/tC). This estimate was mainly based on Eyre et al. (1999) – 'the most sophisticated' estimate (their words) – and was suggested to rise at £1/tC for each subsequent year.

Pearce (2003) reviewed the studies in Clarkson and Deyes (2002) and five more peer-reviewed studies, concluding that £3–£6/tC ($4.5–$9/tC) was the relevant range without equity weighting, and £3–£15/tC ($4.5–$22/tC) with equity weighting.[2] Employing time varying discount rates expanded the range to £4–£27/tC ($6–$40/tC). This much lower estimate is mainly attributed to the consideration of adaptive behavior.

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[1] Applying a conversion rate of 1.5 US $ per UK £, as the approximate average exchange rate in 2000. The same applies to other conversions.
[2] Equity weighting is a process which accounts for the diminishing marginal utility of income—the fact that a pound is less valuable to a rich person than to a poor person. Equity weighting implies that a financial loss suffered by a poor person is weighted more than an identical financial loss suffered by a rich person.

In a recent paper, Tol (2005) gathers 103 estimates from 28 published studies to form a 'probability density function'.[3] The mode is \$2/tC, the median \$14/tC, the mean \$93/tC, and the 95 percentile \$350/tC. The conclusion is that the marginal damage costs of carbon dioxide emissions are unlikely to exceed \$50/tC, under standard assumptions about discounting and aggregation, and are probably much smaller.

The enormous range of estimates in the SCC reflects both the sheer size of the uncertainties in our understanding of future climate change, future socioeconomic variables and also the particular ethical parameters adopted in each model. Drivers of variability between model estimates can be grouped into the following categories:

- *Scientific uncertainties*: Uncertainties about present and future emissions and the impacts under different emission scenarios. More detailed discussions of these uncertainties can be found in the Third Assessment Report (TAR) by IPCC (IPCC, 2001). A particular area of concern is the risk of low-probability catastrophes (such as the collapse of the West-Antarctic ice sheet and the shut-down of the thermohaline circulation).
- *Economic and policy uncertainties*: The assumed rates of economic growth and emission scenarios have a significant impact on the outcome, as does the process by which monetary values are estimated for non-market impacts— the process of placing a value on the loss of life is still debated, for instance.
- *Ethical value judgments*: The aggregation of values across time and regions depend on the choice of a discounting scheme and equity weighting scheme, respectively. This choice is partly a matter of ethical judgment and 'will likely remain, an unresolved question in economics' (IPCC, 1996).

The discount rate sits as a prince among these various drivers of variability between estimates. Understanding the theory behind social discounting has become a necessity for competent policy making in climate change, and with good reason. The next section provides an overview of that theory.

3. Social discounting theory

3.1. The social discount rate

The discount rate employed by the government in evaluating projects and policies over time is called the social discount rate. Various conceptual foundations have been proposed for the social discount rate, including the market rate of interest, the social opportunity cost of investment and the consumption rate of interest (Lind, 1982; Pearce and Ulph, 1999). In an idealized economy, where there are no externalities, taxes or market imperfections of any description, these various rates will be identical in equilibrium. However, no real economy satisfies these assumptions, so the debate about the correct

conceptual foundation for the social discount rate matters. Happily, there is now a consensus that the social discount rate should be based on the 'social rate of time preference' (SRTP), which is the value society attaches to present consumption relative to future consumption. More precisely, the SRTP is the 'rate of fall in the social value of *consumption* by the public' (Pearce and Ulph, 1999).

The SRTP may be estimated by decomposing it into composite parts and estimating the parameters for each part separately. Postulating a social utility function permits decomposition of the social rate of time preference according to:

$$s = \rho + \mu g \tag{1}$$

where s is the SRTP, ρ the 'pure rate of time preference' (PRTP), μ the income elasticity of the marginal utility and g the growth rate of per capita real consumption.

The PRTP is the 'utility discount rate', which reflects our time preference for utility. Estimates of utility discount rates for individuals are almost always positive – an estimate of 1.5% is considered plausible for the UK for instance (HM Treasury, 2003) – for the simple reason that humans prefer good things to come earlier rather than later. Given the inevitability of death for individuals, a preference for benefits to accrue earlier rather than later is entirely sensible. At the social level, however, the arguments are more nuanced, and indeed whether or not the PRTP should be equal zero has been debated by philosophers and economists for decades. Cline (2004), for example, proposes to use a zero PRTP in evaluating climate change policies. Reasonable ethical considerations suggest using a zero PRTP—a positive PRTP involves placing a lower weight on the welfare of future generations, which is impartial and contrary to inter-generational equity. However, there are also persuasive arguments for employing a very small positive PRTP. Hepburn (2006) provides a review of the issues.

The income elasticity of marginal utility, μ, measures the rate of change of the utility derived from an extra unit of income as our income level increases. The literature suggests that this value is around unity (e.g. Cowell and Gardiner, 1999; OXERA, 2002). This implies that an extra pound to a generation that has twice the consumption of the current one will only bring half as much utility to that generation.

The growth rate of per capita consumption, g, varies from country to country. Predictions are usually based on the observation of past trends, so a rate of 2% per annum is broadly accurate for the UK. Putting all these values together, HM Treasury (2003) estimates that a plausible social rate of time preference for the UK is 3.5%.

3.2. Problems with constant discount rates

The social discount *rate* measures the annual rate of decline in the discount *factor* placed on future cash flows. The two are connected by the equation:

$$d_t = \frac{1}{(1+s)^t} \tag{2}$$

where d_t is the discount factor at time t and s the social discount rate. As such, a constant social discount rate implies that the discount factor declines exponentially. The effect of this can be illustrated by a simple example. Consider being

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[3] As Stainforth et al. (2005) note in the context of physical climate models, however, it is impossible to provide an objective probability density function due to the lack of adequate observational constraints.

paid £100 at some point in the distant future. At a discount rate of 3%, the 'present value' of £100 is worth: £23 at year 50; £5.2 at year 100; and £0.27 at year 200.

In other words, conventional discounting drastically reduces the weight placed on consumption flows in 200 years time, meaning that impacts in the far future are essentially irrelevant to decisions made today. While this might be entirely accurate for individuals (who will no longer be alive), it is unlikely to be a satisfactory basis for public policy making. As Weitzman (1998) states, 'to think about the distant future in terms of standard discounting is to have an uneasy intuitive feeling that something is wrong, somewhere'. This is also contrary to the goal of sustainable development, which requires the welfare of far-distant future generations to be taken into account. One solution to the problem of long-term discounting is to employ a discount rate that declines with the time horizon.

3.3. Rationales for declining discount rates

Declining discount rates increase the discount factor (hence the weight placed) on future values, compared with conventional discounting. Far from being an ad hoc solution, declining discount rates (DDR) are supported by ample evidence both empirically and theoretically, as described in Pearce et al. (2003) and Groom et al. (2005).

3.3.1. Hyperbolic discounting
There is relatively strong evidence that individuals' discount rates decline with time, following a hyperbolic path (Frederick et al., 2002). To illustrate, people generally consider there to be a significant difference between: (i) a 1-year delay in consumption now and (ii) a 1-year delay in consumption in 50 years time. Postponing consumption now appears to be significantly less appealing than postponing it for an equal amount of time in 50 years from now. In other words, the weight we place on an extra year in the future is declining with time.

Hyperbolic discounting means that the discount *factor* declines as a hyperbolic function of time, as compared with an exponential function conventionally. A general function proposed by Loewenstein and Prelec (1992) is as follows:

$$d_t = \frac{1}{(1+kt)^{h/k}} \qquad (3)$$

where d_t is the discount *factor* and h 'time perception'. If $h = 0$, individual time periods are perceived as passing extremely fast. As h tends to ∞, time is not perceived to pass at all. The parameter k measures how much the hyperbolic discounting function deviates from the standard exponential model. d_t approaches the exponential function when k approaches 0.

If social decisions should reflect individuals' choices, then hyperbolic discounting should be considered. But hyperbolic discounting is not without problems. As with almost all other forms of time-varying discount rates, time-inconsistency is one problem, which will be discussed in more detail later. Another problem with hyperbolic discounting is that the parameters in Eq. (3) that are measured empirically imply very large initial discount rates, sometimes as high as 30–40%, although the rates are falling rapidly afterwards. Such high

initial rates do not seem reasonable for practical social decision making.

3.3.2. Uncertainties about future economic conditions
Weitzman (1998, 2001), among others, has pointed out that if the appropriate discount rate for the distant future is uncertain, the appropriate course of action is to establish some plausible distribution of discount rates, determine the appropriate time profile of discount factors for each discount rate, and then find a risk-adjusted average of these discount *factors*, called the 'certainty-equivalent discount factor' (CEDF). Working backwards from the CEDF one can determine the corresponding 'certainty-equivalent discount rate' (CEDR) at each point of the time horizon. It turns out that the appropriate CEDR is declining over time. This can be explained by the example below.

Consider a world in which one of three discount rates will be appropriate for the indefinite future: 1%, 3% and 5%, each with an equal probability of 1/3. Then the certainty-equivalent discount factors ($CEDF_t$) and the implicit discount rates ($CEDR_t$) over the time horizon should be calculated as:

$$CEDF_t = \frac{1}{(1 + CEDR_t)}$$
$$= \frac{1}{3}\left[\frac{1}{(1+0.01)^t} + \frac{1}{(1+0.03)^t} + \frac{1}{(1+0.05)^t}\right] \qquad (4)$$

The discount factor corresponding to each possible discount rate is falling exponentially, in the same way as in conventional constant discounting, while the CEDR is declining. Numerical results are shown in Table 1.

Weitzman further shows that the lower limit and asymptote of the CEDR is the lowest possible discount rate (1% in the example above). The reason for the decline of CEDR is that exponential discounting actually reduces the weight of higher discount rates as time goes by because their respective discount factors fall faster. In Table 1, the discount factors based on 1% becomes more dominant in the weighted sum as time goes along. Hence the CEDR falls asymptotically to 1%.

The shape and speed of the decline in the certainty-equivalent discount rate, of course, depends entirely upon the initially assumed probability distribution of discount rates. Based on a survey of over 2000 economists,[4] Weitzman (2001) concludes (somewhat conveniently) that the underlying distribution of discount rates follows a Gamma distribution, in which case the certainty-equivalent discount rate is given by:

$$R(t) = \frac{\alpha}{1 + t\beta^2/\alpha} \qquad (5)$$

where α and β denote the mean and standard deviation of the Gamma distribution, respectively. While Dasgupta (2001) expresses several cogent criticisms of this exercise, nevertheless if these different opinions about the 'correct' social discount rate can indeed by employed as a measure of the

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[4] The survey asked: 'Taking all relevant considerations into account, what real interest rate do you think should be used to discount over time the (expected) benefits and (expected) costs of projects being proposed to mitigate the possible effects of global climate change?'

Table 1 – A numerical example of declining discount rates					
Discount rates	Discount factors in period t				
	10	50	100	200	500
1% ($p_1 = 1/3$)	0.905	0.608	0.370	0.137	0.007
3% ($p_2 = 1/3$)	0.744	0.228	0.052	0.003	0.000
5% ($p_3 = 1/3$)	0.614	0.087	0.008	0.000	0.000
Certainty-equivalent discount factor	0.754	0.308	0.143	0.046	0.002
Certainty-equivalent discount rate (%)[a]	2.86	2.38	1.96	1.55	1.22

[a] This is actually the 'average' certainty-equivalent discount rate. The 'marginal' CEDR, which is calculated slightly differently, but on the same principle, also falls with time, and more quickly.

underlying uncertainty in the discount rate, then this survey result is worth examining.

Another uncertainty that leads to DDR is uncertainty about current and future growth rate of consumption and the economy (recall the parameters g in Eq. (1)), which has been examined by Gollier (2002a,b). Gollier finds that whether the schedule of discount rates is flat, declining or increasing over time depends on the assumptions concerning future economic growth, g and the coefficient of relative risk aversion, μ. In settings where $g < 0$ cannot be ruled out (cf., Tol, 2003), in order to ensure that the discount rates are declining requires restrictions on the fifth derivative of the utility function, which is obviously impossible to test in the near future. However, the point underlying both Weitzman and Gollier's theories is that if there are uncertainties in the discount rate, or any part thereof, the implicit certainty-equivalent discount rate may be declining through time.

Assuming that the past is informative of the future and that interest rates are persistent, Newell and Pizer (2003) try to operationalise Weitzman's (2001) work. They characterize interest rate uncertainty econometrically by estimating a reduced form time series process using 2 centuries of US interest data. Two models are used: the mean reverting and the random walk model. Building upon this idea, Groom et al. (2004) further explore the impact of model selection on the estimation of declining discount rates. They use four models, two of which allow for the change of parameters in the model overtime, i.e., the switching of interest rate from one regime to another.

3.3.3. Intergenerational equity

Li and Lofgren (2000) suppose that there are two different individuals ('utility streams') in the society, a utilitarian and a conservationist. They have identical utility function, with consumption and resource stock as arguments. The difference between them is that they have different PRTP's. The overall societal objective is to maximize a weighted sum of their utilities. The result of weighting is similar to that of Weitzman's discounting—the individual with lower discount rate is given dominant weight as time goes by and the collective discount rate is declining. The technical difficulty with applying this approach is choosing a discount rate for both person and the weight to place on them.

3.3.4. Heterogeneous time preferences

Gollier and Zeckhauser (2003) demonstrate that, in order to maximize collective welfare, the social planner of a group should employ a time variable discount rate when individuals have heterogeneous but constant rates of impatience (that is,

when ρ in Eq. (1) is different for different individuals, but each individual ρ is constant over time). More specifically, if individuals exhibit decreasing absolute risk aversion, the collective PRTP of the group is declining over time. There is plenty of empirical evidence supporting the claim that different people have different rates of time preference. Warner and Pleeter (2001), for instance, found that individual discount rates can vary between 0% and 30%. Moreover, decreasing absolute risk aversion is an entirely plausible assumption given that the share of wealth invested in risky assets increases with income in both developed and developing countries (Ogaki and Zhang, 2000).

3.3.5. Problems with declining discount rates

Although DDR provides a solution to the problem of long-term discounting, employing them may solve this problem only to create another problem for policymakers. Employing a social discount rate that varies through time can generate 'time inconsistency', which refers to the situation where plans made at one point in time are contradicted by later behaviour (even if nothing has changed except the passage of time). Ramsey (1928) observed that this may be a problem, and Strotz (1956) first analyzed the implications. Hepburn (2005) provides an axiomatic statement of the types of discounting function that generate time inconsistency.

Faced with time inconsistent plans, the policymaker can respond in one of three ways. It can behave *naively* and ignore the problem, simply relying on the (false) belief that future policymakers will implement the plan, despite the fact that they have every incentive to deviate from it. Second, it can attempt to *commit* future policymakers to its plans by finding a mechanism that ensures that continuing to implement the plan is always optimal. In the absence of such a commitment mechanism, the policymaker can behave in a *sophisticated* manner, taking into account how future policymakers will

Table 2 – The declining long-term discount rate in the UK Green Book 2003	
Period of years	Discount rate (%)
0–30	3.5
31–75	3.0
76–125	2.5
126–200	2.0
201–300	1.5
301+	1.0

Source: HM Treasury (2003).

Table 3 – Some previous estimates on the effects of DDR on SCC			
Source	Declining scheme	Time horizon	SCC estimate ($/tC)
Nordhaus and Boyer (2000)	$P_0 = 3\%$, declining over time	2300	5.9
Newell and Pizer (2003)	$S_0 = 2\%$, random walk model	2400	33.8
	$S_0 = 4\%$, random walk model	2400	10.4
	$S_0 = 7\%$, random walk model	2400	2.9
	$S_0 = 2\%$, mean-reverting model	2400	23.3
	$S_0 = 4\%$, mean-reverting model	2400	6.5
	$S_0 = 7\%$, mean-reverting model	2400	1.8
Tol and Heinzow (2003)	$P_0 = 3\%$, Weitzman discounting, falls to 1% after 200, 100, 50, 25 years	2200	2.1, 3.5, 5.7 and 8.0, respectively

Note: P_0 and S_0 refer to the initial pure rate of time preference and social rate of time preference, respectively. Source: adapted from Tol (2005).

behave, and developing a plan that is an optimal response to future planners' optimal responses. If policymakers are likely to respond to time inconsistency with naivety, then employing declining discount rates might be dangerous (Hepburn, 2003). If the response is sophistication or commitment, there is nothing to worry about. Moreover, although Heal (1998) shows that many types of declining discount rates result in time inconsistency, one can always find a declining schedule of social discount rates that avoids the problem in the first place.

3.4. Applications of declining discount rates

The most significant use of declining discount rates in policy making is seen in the UK HM Treasury (2003) Green Book, where the recommended social discount rate is declining with time according to Table 2.

The recommendation in the Green Book is mainly based on studies that apply the uncertainty theory, such as that of Newell and Pizer (2003). In their study, 2 centuries of US interest rate data are used to quantify the effect of uncertainty. Under the random walk model, the certainty-equivalent discount rate falls continuously from 4% to 2% after 100 years, 1% after 200 years and 0.5% after 300 years. Applying this scheme to an integrated assessment model, the DICE model (Nordhaus, 1990, 1994; Nordhaus and Boyer, 2000), it is found the SCC is almost doubled. Other rough sensitivity studies on the effect of declining discount rates on the SCC are listed in Table 3.

While these studies do give a concrete number to indicate the effect of DDR, they apply different integrated assessment models and use different time horizons. Hence they do not provide a convenient setting for comparison of the effects of different DDR schemes and their results. Furthermore, the declining schemes they test are rather limited and the parameterizations of the schemes are rather simple. This paper conducts a more complete sensitivity study, comparing the effect of several different declining discount rates schemes using one integrated assessment model.

4. Methodology

4.1. FUND 2.8

The Climate Framework for Uncertainty, Negotiation and Distribution (FUND) is an integrated assessment model

established in the late 1990s to estimate the global impacts of greenhouse gas emissions, amongst other things. Key references are Link and Tol (2004) and Tol (1999a,b, 2002a,b).[5] The version employed in this research, FUND 2.8, divides the world into 16 geographical regions and runs from 1950 to 2300 in intervals of one year. The model extends back to 1950 so it can be initialized with past data. As such, the period from 1950–1990 is based on historical observations while that from 1990–2100 is based on the default FUND scenario, which lies somewhere in between the IS92a and IS92f (Tol, 2005). Exogenous scenarios including economic growth and population growth forecasts, and the CO_2 emissions profile are predicted for each region in each period. Impacts after 2100 are extrapolated from the trends in 2050–2100, incorporating a gradual shift to a steady state of population and economic growth. Such extrapolations are so far into the future that these scenarios will inevitably be incorrect, but the most one can ask is that they are based upon plausible models of the economy and the climate, and that they continue to adapt with developments in the physical and social sciences.

Estimates of the marginal damage from carbon dioxide emissions are obtained by running the model twice, where the second run incorporates an additional ton of carbon. The differences between the damages per region, per year, in the two runs are calculated expressed as D_{it}, the marginal damages caused by the emission of 1 t of carbon emission. These damages are then discounted back to present values using the social discount rate s according to:

$$V_i = \sum_0^T D_{it}(1+s)^{-t} \tag{6}$$

where V_i is the present value of damages in region i. The present value damages of each region V_i's are added together.

The social discount rate employed in FUND is the social rate of time preference (SRTP), constructed using Eq. (1). In FUND 2.8, the PRTP is constant and three different values: 0%, 1% and 3% are examined. It is assumed that μ is constant and homogeneous for all regions, taking a value of 1.0. The growth rates of per capita GDP, g, vary across different regions and over time, according to the exogenous economic scenario employed. As such, a separate SRTP is calculated for each region in each year, based on the model prediction of GDP growth and population level. From this perspective, FUND

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[5] Further references and the model code can be found at http://www.uni-hamburg.de/Wiss/FB/15/Sustainability/fund.html.

already applies a time-varying social discount rates scheme, although whether or not the discount rates decline depends upon the specific assumptions about per capita growth rates for each region.

4.2. Incorporating declining discount rates into FUND

Of the various justifications for declining discount rates proposed above in Section 3.3, the most significant schemes are those based upon uncertainty in future socioeconomic conditions. For this reason, we examine four sets of schemes based on economic uncertainty, namely: (1) The scheme in the HM Treasury (2003) Green Book; (2) Gamma discounting and the step-function approximation in Weitzman (2001); (3) Discounting when the rate of economic growth is uncertain, as per Gollier (2002a,b); and (4) The econometrically estimated discounting model as per Groom et al. (2004).

Schemes based on hyperbolic discounting were ignored because initial discount rates of up to 30% are simply unrealistic for use in social policy. Declining discount rates based upon the formulation in Li and Lofgren (2000) were avoided given the arbitrariness of selecting weights to be placed on the conservationist and the utilitarian. Gollier and Zeckhauser's (2003) heterogeneous theory is novel and sound, but it is not easy to quantify the heterogeneity in a practical way.

4.2.1. UK Green Book discounting

The *Green Book: Appraisal and Evaluation in Central Government*, published by the UK HM Treasury in 2003 is an update of its previous versions. The document provides guidance on public project appraisals 'before significant funds are committed' (HM Treasury, 2003). A significant feature of the Green Book is that for the first time, the declining discounting scheme discussed above was introduced for the evaluation of projects with long-term impacts (see Table 2).

To update FUND 2.8 with the Green Book discounting scheme involved forcing the social discount rates specified in HM Treasury (2003) for the world as a whole for each year after 2000. In other words, one social discount rate was used for the whole world in each year, rather than using region-specific discount rates as in the default setting of the FUND model. Of course, applying a UK-based social discount rate to other regions of the world does not reflect the fact that other regions have different growth rates and possibly also different rates of time preference, as discussed in Section 3.3.4 above. Indeed, the differences in the social discount rates might partly explain the varying attitudes of each country on the Kyoto Protocol.

Nevertheless, as a sensitivity analysis it is an interesting exercise and, moreover, the scenarios for economic growth and population in FUND 2.8 start to converge after 2100. This implies that after 2100, using a global discount rate does not produce significant deviations from using region-specific ones, although it is worth noting the potential significant differences of discount rates in different regions.

4.2.2. Gamma discounting

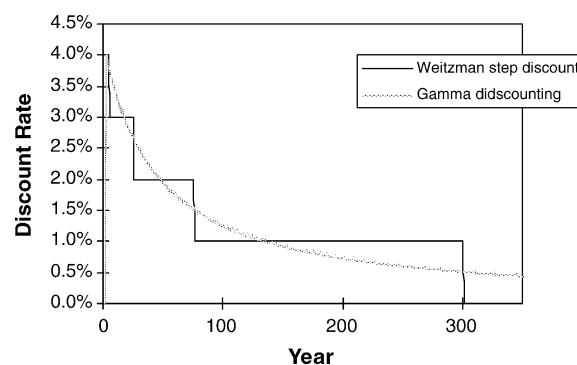As mentioned above, in order to estimate the current uncertainty about the discount rate to be used on the far

Fig. 1 – A comparison between the two Weitzman schemes. Source: adapted from Weitzman (2001).

distant future, Weitzman conducted a survey of over 2000 economists around the world. The 2160 responses, once they were truncated at 0%, approximately conform to a gamma distribution.

Based on these results, Weitzman proposes two rounded-off average values as parameters for the gamma distribution: $\alpha = 4\%$ per annum and $\beta = 3\%$ per annum. Implementing the Weitzman discounting in FUND involves applying an SRTP for the world in each year, where the SRTP is given by substituting $\alpha = 4\%$ and $\beta = 3\%$ into Eq. (5) to yield:

$$R(t) = \frac{4}{100 + 2.25t} \tag{7}$$

Weitzman also suggests a step-declining schedule to approximate the gamma discounting function (see Table 4 and Fig. 1). A comparison between Weitzman and the Green Book schemes is shown in Fig. 2. Since a close match between the equation and step-declining scheme would further strengthen the applicability of Weitzman discounting, we also test the Weitzman step-declining scheme.

4.2.3. Gollier discounting

In the previous approaches, the SRTP as a whole is taken as uncertain, and the certainty-equivalent SRTP is employed as the social discount rate. Gollier (2002a,b) takes a different
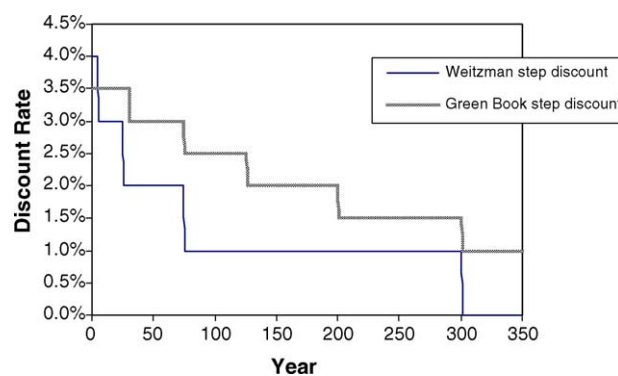

Fig. 2 – A comparison between Weitzman and Green Book step-declining schemes. Source: adapted from Weitzman (2001) and HM Treasury (2003).

Table 4 – The Weitzman step decline schedule to approximate gamma discounting	
Period of years	Discount rate (%)
1–5	4
6–25	3
26–75	2
76–300	1
301+	0
Source: Weitzman (2001).	

approach by breaking down the SRTP and treating the consumption growth (g) as uncertain. Gollier's approach involves much more complicated specifications about individual utility functions and risk preferences. As such, various conditions need to be satisfied before declining social discount rates emerge. Since it is unrealistic to test Gollier's assumptions, this paper implements DDR from growth uncertainties by using the central idea of Gollier's paper and adapting it in a more practical context.

The central idea is that if future growth rates are uncertain, the certainty-equivalent discount factor will be an average of the discount factors corresponding to each possible growth rate. This underlying logic is identical to Weitzman (1998), except that here the growth rate, rather than the discount rate itself, is assumed to be uncertain.

To implement this approach, the regional growth rates in FUND were assumed to be uncertain, while the PRTP is assumed to be constant. A simple yet illustrative way of incorporating uncertainty in future economic conditions is to set an upper and lower boundary for the per capita income growth rate, using the original forecast growth rates as the mean estimates. To set lower and upper bounds (denoted g_l and g_u, respectively) we assume that growth rates are equally likely to be 1% above or below the mean estimate, for all years and all regions. This specification is somewhat ad hoc, and therefore it is more illustrative than conclusive. However, we consider it as a useful first step. For instance, if the original growth rate for a specific region in a specific year is $g_0 = 4\%$, then we now assume that the growth rate for that year is equally likely to be $g_l = 3\%$ and $g_u = 5\%$.

These two new growth rates can be used to calculate new discount rates (SRTP) for that year, according to Eq. (1):

$$\text{SRTP}_l = \text{PRTP} + \mu g_l$$
$$\text{SRTP}_u = \text{PRTP} + \mu g_u \tag{8}$$

where SRTP_l and SRTP_u are the lower and upper SRTP calculated using the two new growth rates above. The certainty-equivalent SRTP, denoted SRTP_e, can be calculated by working backwards from the certainty-equivalent discount factors, which are simply an unweighted average of the factors corresponding to SRTP_l and SRTP_u.

As an alternative specification of the uncertainty in future growth rates, we also consider a second scheme where we assume that growth rates are roughly bell shaped. Employing the original growth rate in FUND as the mean value, λ, we assume a standard deviation $\sigma = 0.5\%$. Five discrete points are used to approximate the normal distribution. These five points

are: $\lambda - 2.5\sigma$, $\lambda - 1.5\sigma$, $\lambda + 1.5\sigma$, $\lambda + 2.5\sigma$ and λ. Their probabilities are as follows:

- $P(\lambda - 2.5\sigma) = P(\lambda + 2.5\sigma) = 1 - \Phi(3) + \Phi(3) - \Phi(2) = 1 - \Phi(2) = 0.0227$
- $P(\lambda - 1.5\sigma) = P(\lambda + 1.5\sigma) = \Phi(2) - \Phi(1) = 0.9773 - 0.8413 = 0.136$
- $P(\lambda) = 2(\Phi(1) - \Phi(0)) = 2(0.8413 - 0.500) = 0.6826$

where,

$$\Phi(x) = \int_{-\infty}^{x} \frac{1}{(2\pi)^{1/2}} \exp\left(-\frac{1}{2}u^2\right) du$$

the standard normal cumulative distribution function.

With this given discrete distribution, the calculation of a certainty-equivalent discount factor is similar to the first scheme outlined above. Five SRTP's are calculated, which are based on five possible growth rates, where g is the original growth rate in FUND.

$$\begin{aligned}
\text{SRTP}_1 &= \text{PRTP} + \mu(g - 2.5\sigma) \\
\text{SRTP}_2 &= \text{PRTP} + \mu(g - 1.5\sigma) \\
\text{SRTP}_3 &= \text{PRTP} + \mu g \\
\text{SRTP}_4 &= \text{PRTP} + \mu(g + 1.5\sigma) \\
\text{SRTP}_5 &= \text{PRTP} + \mu(g + 2.5\sigma)
\end{aligned} \tag{9}$$

The certainty-equivalent discount factor for each year is calculated by applying these discount factors, each with probability as given above. As before, a certainty-equivalent SRTP can then be calculated for each year in each region.

4.2.4. The 'Regime Switch' model

Groom et al. (2004) used both US and UK interest rate data to estimate a model with regime switches:

$$\begin{aligned}
r_t &= \eta + a_t r_{t-1} + e_t \\
a_t &= \sum_{i=1}^{p} \eta_i a_{t-1} + u_t
\end{aligned} \tag{10}$$

They estimate this model in state space, using the Kalman filter. We use the results from the US data to apply to FUND 2.8, which are as follows (assuming r_t is the SRTP):

$\eta = 0.510$,
$\eta_1 = 0.990$,
$\ln(\sigma_e^2) = -9.158$,
$\ln(\sigma_u^2) = -6.730$,
$r_1 = 4.0$, $a_1 = 0.910$

Using these parameters, the simulations result for 300 years are as follows (Table 5). Once again we use these discount rates for all regions in the world.

Table 5 – Simulation results for the State Space model	
Year	Discount rate (%)
1	4.00
20	2.79
40	2.59
60	2.38
80	2.23
100	2.10
150	1.91
200	1.79
300	1.67
Source: Groom et al. (2004).	

Table 6 – Summary of DDR schemes implemented in FUND 2.8	
Scheme name	Implementation method
Green Book step-declining scheme	Employ a global SRTP in each year after 2000, which declines according to the step-declining scheme in the UK Green Book
Weitzman step-declining scheme	Employ a global SRTP in each year after 2000, which declines according to the step-declining scheme in Weitzman (2001)
Gamma discounting	Employ a global SRTP in each year after 2000, which declines according to the continuous gamma distribution in Weitzman (2001)
Gollier discounting: scheme 1	For each region, employ a certainty-equivalent SRTP derived by assuming the regional growth rate is equally likely to be 1% above or below the original forecast growth rate.
Gollier discounting: scheme 2	For each region, calculate another certainty-equivalent SRTP using five possible growth rates. Apply the new SRTP instead of the original one.
Regime Switch Model	Use a global SRTP in each year after 2000. The SRTP declines in accordance with the simulation results of the Regime Switch model, based on the US interest rate data.

4.3. Summary

The six discounting schemes discussed above will be implemented in FUND 2.8, according to the method outlined in Table 6.

5. Results

Results, in the form of the estimated social cost of carbon expressed in 1995 US dollars/t of carbon emissions, are presented in Tables 7 and 8 below. SCC in 2005 prices are also listed for comparison, assuming an average inflation rate of 2.0% from 1995 to 2005. Table 7 gives estimates of the social cost of carbon from FUND for three pure rates of time preference, where the corresponding SRTP is a function of the default economic growth scenarios.

The SCC from a constant PRTP of 3% is negative, implying that an extra ton of carbon emitted today will lead to net benefits. This result arises from the emissions damage profile in FUND—near-term effects are dominated by benefits (e.g. increase of agricultural productivity) while damages are in the far-distance future, which are discounted more heavily.

6. Discussion

6.1. Effects of declining discount rates

The least surprising result from Table 8 is that declining discount rates increase estimates of the SCC. However, the precise effect of declining discount rates on SCC estimates is more variable than one would anticipate from the literature. Newell and Pizer (2003), for instance, suggests that time-varying discount rates could raise the SCC by about 80% when

initial SRTP = 4%. The calculations in Pearce et al. (2003) suggest that moving from a constant SRTP = 4% to a scheme similar to the HM Treasury Green Book would increase the SCC by about 50%, and that employing Gamma discounting increases the SCC by factor of 3. Here, in contrast, moving from a constant SRTP = 3.5% to the Green Book discount rates increases the SCC by 170%, and employing Gamma discounting increases the SCC by a factor of 40.

In other words, our results suggest that the impact of declining discount rates may be more significant than previously expected in the literature. Why do our results differ from previously published estimates? Part of the reason is that the damage profile through time from FUND 2.8 shows more pronounced early benefits than other models. A result of this is that the relative weight placed on impacts now and impacts in the far-distant future is especially important. Another result of this is that base case estimates of the SCC in FUND tend to be lower—the increase by the factor of 40 is from an extremely low initial estimate of $2/tC.

Four other conclusions follow from the results presented in Table 8. First, although declining discount schemes raise the value of SCC, they do not push the SCC to a very high level (without equity weighting). For instance, even though the UK Green Book discounting scheme raises the value of SCC by 170%, the resulting SCC estimate of $18/tC ($22/tC in 2005 prices) is still much smaller than the £70/tC ($116/tC in 2005 prices) recommended by Clarkson and Deyes (2002). The only scheme that gives a higher number than the £70/tC is the Gollier scheme based on uncertainties of growth, combined with a constant PRTP of 0%.

Second, the results from the gamma discounting and the Weitzman step-declining scheme are almost identical, indicating that Weitzman (2001) did an admirable job of approximating the continuous discount rate with the step-function. It follows that the step-declining scheme is a good guide for policy and practical implementation if Weitzman's rationale and particular estimates for declining discount rates were to be adopted.

Third, comparing the results from the two step-declining schemes – the Green Book discounting scheme and the Weitzman scheme – indicates that the shift to declining discount rates in the UK has been a relatively modest affair. The Weitzman scheme declines significantly more rapidly

Table 7 – SCC from constant PRTPs		
Discounting scheme	SCC ($/tC) (in 1995 prices)	SCC ($/tC) (in 2005 prices)
Constant PRTP = 0%	58	71
Constant PRTP = 1%	11	13
Constant PRTP = 3%	−2.3	−2.8

Table 8 – Results of 5 DDR schemes tested on FUND 2.8		
DDR schemes	SCC ($/tC) (in 1995 prices)	SCC ($/tC) (in 2005 prices)
Green Book step-declining scheme	18	22
Constant SRTP = 3.5%	6.6	8.1
Weitzman step-discounting scheme	88	107
Constant SRTP = 4%	2.1	2.6
Gamma discounting	88	107
Constant SRTP = 4%	2.1	2.6
Gollier discounting scheme 1		
Constant PRTP = 0%	185	226
Constant PRTP = 1%	29	35
Constant PRTP = 3%	−1.3	−1.6
Gollier discounting scheme 2		
Constant PRTP = 0%	85	104
Constant PRTP = 1%	15	18
Constant PRTP = 3%	−2.1	−2.6
Regime Switch Model	35	43

than the Green Book scheme, and estimates of the SCC are correspondingly higher, as summarized in Fig. 3.

Fourth, comparing the results in Table 8 for the two Gollier schemes reveals the significance of the precise specification of economic uncertainty. The SCC estimates from scheme 1 – where the probability density was assumed to be spread equally between two points ±1% from the original growth rate – are significantly higher than in scheme 2, where the spread was smaller. The application of the Regime Switch model substantiates the same point: the Regime Switch model allows for big changes in the generating mechanism of discount rates (i.e. economic uncertainty is accounted for in the model) and the SCC from the model is higher than the Gollier scheme 2.

Note also that the higher the PRTP, the smaller the impact of accounting for uncertain growth on the SCC. This is an intuitive result: the higher the PRTP, the smaller the relative impact of the growth rate in Eq. (1), and hence the smaller the impact of uncertainty on the final outcome. In other words, the more patient we consider ourselves to be (lower PRTP), the more important it is to account for uncertainty in future economic growth.
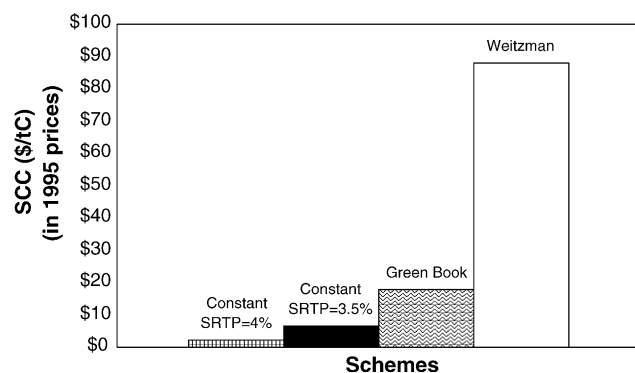
Fig. 3 – A comparison between SCCs from two step-declining schemes.

6.2. Some practical implications

As declining discount rates increase the SCC, it follows that policies on climate change are more likely to pass a cost-benefit analysis.[6] Consider the UK's commitment to the Kyoto Protocol. According to Pearce (2003), the marginal cost of control under the Kyoto commitment is £45/tC ($74/tC in 2005 prices). If ancillary benefits are not considered, then there are only four combinations that would make this commitment pass a CBA, viz. the two Weitzman schemes and two of the Gollier combinations based on growth uncertainty, combined with a PRTP of 0%. Although all the DDR schemes produce an increase in the SCC estimates, only four of the resulting values of SCC would justify the Kyoto commitment in terms of economic efficiency. If ancillary benefits are included, and are assumed to be £35/tC (Pearce, 2003), then almost all the results here (except two) would make the UK's commitment to Kyoto pass CBA.

Such comparisons, however, are fairly approximate, and we leave it to other research to more accurately estimate the marginal costs of control – £45/tC might also be an over-estimate if 'flexibility mechanisms' (e.g. emissions trading) are adopted – and to fully incorporate other relevant decision variables on the damage side, such as equity weighting, uncertainty in the climate sensitivity parameter, and cata-strophic impacts. Moreover, there are obviously ethical and political economic reasons, beyond the simple cost and benefits, which would tend to support efforts to foster international collective action on a global public goods challenge as complex as climate change.

7. Conclusions

Three major conclusions follow from the sensitivity analysis presented in this paper. First, our results indicate that declining discount rates increase estimates of the SCC in a more variable manner than previously reported in the literature. Depending upon the particular discounting scheme, increases from only 10% up to a factor of 40 were found. A key conclusion is that general statements such as 'declining discount rates increase the SCC by approximately 100%' may well be inappropriate, for the actual increase can vary dramatically with the particular discounting scheme assumed.

Second, in FUND 2.8 uncertainty in discounting alone does not drive up the SCC to a very high level, e.g. the £70/tC suggested in Clarkson and Deyes (2002). This is partly a function of the interaction between the discounting schemes and the damage profile in FUND 2.8, which some critiques regard as being optimistic about adaptation.

Third, relating to policy appraisal, the results in this paper suggest that if the marginal cost of £45/tC is used as the cost of climate change related projects in the UK, only a few of the DDR schemes would produce an SCC that will make the UK's commitment to Kyoto pass CBA.

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[6] Note that the costs of emission abatement are less sensitive to the discount rate than the SCC.

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REFERENCES

Clarkson, R., Deyes, K., 2002. Estimating the Social Cost of Carbon Emissions. Government Economic Service Working Paper. HM Treasury, London.

Cline, W.R., 2004. Meeting the challenge of global warming. In: Lomborg, B. (Ed.), Global Crises, Global solutions. Cambridge University Press, Cambridge.

Cowell, F.A., Gardiner, K., 1999. Welfare weights, STICERD, London School of Economics. Economics Research Paper 20.

Dasgupta, P., 2001. Human Wellbeing and the Natural Environment. Oxford University Press, Oxford, pp. 187–190.

Diamond, P., Hasuman, J., 1994. Contingent valuation: is some number better than no number? J. Econ. Perspect. 8 (4), 45–64.

Eyre, N., Downing, T.E., Hoekstra, R., Rennings, K., Tol, R.S.J., 1999. Global warming damages. Final Report of the ExternE Global Warming Sub-Task (September 98), DGXII, European Commission, Brussels.

Frederick, S., Loewenstein, G., O'Donoghue, T., 2002. Time discounting and time preference: a critical review. J. Econ. Lit. 40 (2), 351–401.

Gollier, C., 2002a. Time horizon and the discount rate. J. Econ. Theory 107, 463–473.

Gollier, C., 2002b. Discounting an uncertain future. J. Public Econ. 85 (2), 149–166.

Gollier, C., Zeckhauser, R., 2003. Collective investment decision making with heterogeneous time preferences. NBER Working Paper 9629. National Bureau of Economic Research (NBER), Cambridge, Massachusetts.

Groom, B., Koundour, P., Panopoulou, E., Pantalidis, T., 2004. Model selection for estimating certainty equivalent discount rates. University College London Discussion Paper 04–02.

Groom, B., Hepburn, C., Koundouri, P., Pearce, D., 2005. Discounting the future: the long and the short of it. Environ. Resource Econ. 31 (1), 445–493.

Hanemann, W.M., 1994. Valuing the environment through contingent valuation. J. Econ. Perspect. 8 (4), 19–43.

Heal, G., 1998. Valuing the Future: Economic Theory and Sustainability. Columbia University Press, New York.

Hepburn, C., 2003. Hyperbolic discounting and resource collapse. Oxford University, Department of Economics, Working Paper 159, Oxford.

Hepburn, C., 2005. Concerning the future: declining discount rates and intergenerational equity. Doctoral Thesis, Oxford University.

Hepburn, C., 2006. Valuing the far-off future: discounting and its alternatives. In: Atkinson, G., Dietz, S., Neumayer, E. (Eds.), Handbook of Sustainable Development, Cheltenham, Edward Elgar, UK.

Treasury, H.M., 2003. The Greenbook: Appraisal and Evaluation in Central Government. TSO, London.

IPCC (The Intergovernmental Panel for Climate Change), 1996. Economic and Social Dimensions of Climate Change: Summary for Policy Makers. In: Climate Change: 1995, Cambridge University Press, New York.

IPCC (The Intergovernmental Panel for Climate Change), 2001. Climate Change 2001: The Scientific Basis. Cambridge University Press, New York.

Li, C.Z., Lofgren, K.G., 2000. Renewable resources and economic sustainability: a dynamic analysis with heterogeneous time preferences. J. Environ. Econ. Manage. 40, 236–250.

Lind, R.C., 1982. Discounting for Time and Risk in Energy Policy. Resources for the Future, Washington, DC.

Link, P.M., Tol, R.S.J., 2004. Possible economic impacts of a shutdown of the thermohaline circulation: an application of FUND. Portug. Econ. J. 3, 99–114.

Lomborg, B. (Ed.), 2004. Global Crises, Global Solutions. Cambridge University Press, Cambridge.

Loewenstein, G., Prelec, D., 1992. Anomalies in intertemporal choice: evidence and an interpretation. Q. J. Econ. 107, 573–597.

Manne, A.S., 2004. Global climate change: an opponent's notes. In: Lomborg, B. (Ed.), Global Crises, Global Solutions. Cambridge University Press, Cambridge.

Mendelsohn, R., 2004. Opponent paper on climate change. In: Lomborg, B. (Ed.), Global Crises, Global Solutions. Cambridge University Press, Cambridge.

Newell, R.G., Pizer, W.A., 2003. Discounting the distant future: how much do uncertain rates increase valuations? J. Environ. Econ. Manage. 46, 52–71.

Nordhaus, W.D., 1990. To slow or not to slow: the economics of the Greenhouse effect. Econ. J. 101 (407), 920–937.

Nordhaus, W.D., 1994. Managing the Global Commons: the Economics of Climate Change. MIT Press, Cambridge, MA.

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

Ogaki, M., Zhang, Q., 2000. Risk sharing in village India: The Rule of Decreasing Relative Risk Aversion. Ohio State University Working Paper.

OXERA Consulting Ltd., 2002. A social time preference rate for use in long-term discounting. Report to Office of the Deputy Prime Minister. Department for Transport, and DEFRA.

Pearce, D.W., Cline, W.R., Achanta, A., Fankhauser, S., Pachauri, R., Tol, R., Vellinga, P., 1996. The social costs of climate change: Greenhouse damage and the benefits of control. In: Intergovernmental Panel on Climate Change, Climate Change 1995: Economic and Social Dimensions of Climate Change. Cambridge University Press, Cambridge, pp. 183–224.

Pearce, D.W., Ulph, D., 1999. A social discount rate for the United Kingdom. In: Pearce, D.W. (Ed.), Economics and the Environment: Essays in Ecological Economics and Sustainable Development. Edward Elgar, Cheltenham, pp. 268–285.

Pearce, D.W., 2003. The social cost of carbon and its policy implications. Oxford Rev. Econ. Policy 19 (3), 362–384.

Pearce, D.W., Groom, B., Hepburn, C., Koundouri, P., 2003. Valuing the future: recent advances in social discounting. World Econ. 4 (2), 121–141.

Ramsey, F.P., 1928. A mathematical theory of saving. Econ. J. 38, 543–559.

Sachs, J., 2004. Seeking a global solution: the Copenhagen consensus neglects the need to tackle climate change. Nature 430, 725–726.

Stainforth, D.A., Aina, T., Christensen, C., Collins, M., Faull, N., Frame, D.J., Kettleborough, J.A., Knight, S., Martin, A., Murphy, J.M., Piani1, C., Sexton, D., Smith, L.A., Spicer, R.A., Thorpe, A.J., Allen, M.R., 2005. Uncertainty in predictions of the climate response to rising levels of greenhouse gases. Nature 433, 403–406.

Strotz, R., 1956. Myopia and inconsistency in dynamic utility maximisation. Rev. Econ. Studies 23, 163–180.

Thomas, H.A., 1963. Animal farm: a mathematical model for the discussion of social standards for control of environment. Q. J. Econ. 7 (1), 143–148.

Tol, R.S.J., 1999a. The marginal costs of Greenhouse gas emissions. Energy J. 20 (1), 61–81.

Tol, R.S.J., 1999b. Time discounting and optimal control of climate change: an application of FUND. Clim. Change 41 (3–4), 351–362.

Tol, R.S.J., 2002a. Estimates of the damage costs of climate change. Part 1: Benchmark estimates. Environ. Resource Econ. 21 (2), 47–73.

Tol, R.S.J., 2002b. Estimates of the damage costs of climate change. Part II: Dynamic estimates. Environ. Resource Econ. 21 (2), 135–160.

Tol, R.S.J., 2003. Is the uncertainty about climate change too large for expected cost-benefit analysis? Clim. Change 56 (3), 265–289.

Tol, R.S.J., 2005. The marginal damage costs of carbon dioxide emissions: an assessment of the uncertainties. Energy Policy 33 (16), 2064–2074.

Tol, R.S.J., Heinzow, T., 2003. External and sustainability costs of climate. In: Markandya, A. (Ed.), GreenSense Final Report. University of Bath, Bath.

Warner, J.T., Pleeter, S., 2001. The personal discount rate: evidence from military downsizing programs. Am. Econ. Rev. 91 (1), 33–53.

Weitzman, M., 1998. Why the far distant future should be discounted at its lowest possible rate. J. Environ. Econ. Manage. 36, 201–208.

Weitzman, M., 2001. Gamma discounting. Am. Econ. Rev. 91 (1), 261–271.

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