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ABSTRACT

A new and important concept in global warming economics and policy is the social cost of carbon or SCC. This concept represents the economic cost caused by an additional ton of carbon-dioxide emissions or its equivalent. The present study describes the development of the concept as well as its analytical background. We estimate the SCC using an updated version of the RICE-2011 model. Additional concerns are uncertainty about different aspects of global warming as well as the treatment of different countries or generations. The most important results are: First, the estimated social cost of carbon for the current time (2015) including uncertainty, equity weighting, and risk aversion is $44 per ton of carbon (or $12 per ton CO2) in 2005 US$ and international prices). Second, including uncertainty increases the expected value of the SCC by approximately 8 percent. Third, equity weighting generally tends to reduce the SCC. Finally, the major open issue concerning the SCC continues to be the appropriate discount rate.

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A new and important concept that has taken center stage in economic and policy discussions about global warming is the "social cost of carbon" or SCC. This concept represents the economic cost caused by an additional ton of carbon dioxide emissions (or more succinctly carbon) or its equivalent. In a more precise definition, it is the change in the discounted value of the utility of consumption denominated in terms of current consumption per unit of additional emissions. In the language of mathematical programming, the SCC is the shadow price of carbon emissions along a reference path of output, emissions, and climate change.

Estimates of the SCC are a critical ingredient in climate-change policy. They provide policy makers a guidepost to aim for if they are seeking an economically efficient policy for carbon pricing. Another application is for rulemaking where countries do not have comprehensive policies covering all GHGs. In this context, regulators might use the SCC in a calculation of social costs and benefits of policies involving energy or climate-affecting decisions. For example, the US government has undertaken rulemaking proceedings to determine the SCC for use in such areas as subsidies for the installation of low carbon energy sources, regulations requiring energy efficiency standards in buildings and motor vehicles, and rebates for home insulation materials (see the discussion by the U.S. Working Group in US Regulatory Impact Analysis 2010 and also discussed in Greenstone et al. 2011).

We can illustrate the concept in Figure 1. This shows a path of greenhouse gas (GHG) emissions along with a path of a comprehensive measure of economic welfare, such as generalized consumption. We show an increment of emissions in the second period, along with a base and alternative path of consumption. If we take the difference in the value of consumption between the two paths, discount it back to period 2, and then divide it by the increment in emissions, that is the SCC in period 2.

In an optimized climate policy (abstracting away from the deadweight losses of other taxes and the complications due to tax or regulatory distortions), the social cost of carbon will equal the carbon price or the carbon tax. In an uncontrolled regime, the social cost of carbon will generally exceed the (zero) carbon price. There is some confusion about the path along which the SCC should be calculated. It should refer to the *actual* path of emissions and output (or some distribution of that in a stochastic framework), not the uncontrolled path.

I. Analysis of the Social Cost of Carbon in the RICE-2011 Model

The discussion begins with an introduction to the model used to calculate the SCC. Once the modeling details are developed, the precise definition of the SCC can be easily shown. We then present numerical estimates of the SCC.

Background on the RICE-2011 model

The present discussion begins with a calculation of the SCC in the RICE-2011 model. This model is the latest version of a series of models of the economics of global warming, and is an updated version of the model described in Nordhaus (2010). This discussion will present the major elements, and a more complete treatment is contained in Nordhaus (2008, 2010), with the details of the model in the Supplementary Information to Nordhaus (2010).

The RICE model views climate change in the framework of economic growth theory. In a standard neoclassical optimal growth model known as the Ramsey model, society invests in capital goods, thereby reducing consumption today, in order to increase consumption in the future (Ramsey 1928, Koopmans 1965). The RICE model modifies the Ramsey model to include climate investments, which are analogous to capital investments in the mainstream model. That is, we can view concentrations of GHGs as "negative natural capital" and emissions reductions as investments that lower the quantity of that negative capital. Emissions reductions lower consumption today but, by preventing economically harmful climate change, increase consumption possibilities in the future.

The model divides the world into 12 regions. Some are large countries such as the United States or China; others are large multi-country regions such as the European Union or Latin America. Each region is assumed to have a well-defined set of preferences, represented by a social welfare function, and to optimize its consumption, GHG policies, and investment over time. The social welfare function is increasing in the per capita consumption of each generation, with diminishing marginal utility of consumption. The importance of a generation's per capita consumption depends on its relative size. The relative importance of different generations is measured using a pure rate of time preference, and the curvature of the utility function is given by the elasticity of the marginal utility of consumption. These parameters are calibrated to ensure that the real interest rate in the model is close to the average real interest rate and the average real return on capital in real-world markets (Arrow et al 1995, Nordhaus 1994).

The model contains all elements from economics through climate change to damages, and it is specified for 12 regions.

Equations of the RICE-2011 model

The details of the major equations for calculating the SCC are as follows. Begin with a social welfare function, W, that is the discounted sum of the population-weighted utility of per capita consumption. The notation here is that c^j is per capita consumption, L^j is population, and $R^j(t) = (1+\rho)^{-t}$ is the discount factor on utility or welfare, all of which are discussed as we proceed. The weights $\theta^j(t)$ are Negishi weights that are set so that the maximization corresponds to a market equilibrium. The social welfare function is then:

$$(1) \quad W = \sum_{t=1}^{T\,max} \sum_{j=1}^{R} \theta^j(t)\ U^j[c^j(t), L^j(t)]\, R^j(t)$$

The RICE model takes the utility function to be a constant elasticity with respect to consumption of the form $U(c) = c^{1-\alpha} / (1-\alpha)$. Net output, $Q^j(t)$, is a function of gross output, $Y^j(t)$, which is reduced by damages and mitigation costs:

$$(2) \quad Q^j(t) = \Omega^j(t)[1 - \Lambda^j(t)]Y^j(t)$$

In this specification, $Q(t)$ is output net of damages and abatement, $Y(t)$ is gross output, which we take as exogenous for this exposition, but is a function of capital, labor, and technology in the model. The additional variables in the production function are $\Omega(t)$ and $\Lambda(t)$, which represent the damage function and the abatement-cost function, respectively. We take the abatement-cost function as exogenous for our purposes. The damage function is defined as $\Omega(t) = D(t) / [1 + D(t)]$, where

$$(3) \quad D(t) = f_1[T_{AT}(t)] + f_2[SLR(t)] + f_3[M_{AT}(t)]$$
$$\approx \psi_1 T_{AT}(t) + \psi_2 [T_{AT}(t)]^2$$

Equation (3) involves the economic impacts or damages of climate change, which is central to the estimates of the SCC. The damage function in the RICE-2011 model is built up from estimates of the damages of the twelve regions, including assumed sectoral change and underlying income elasticities of different outputs. It includes estimated damages to major sectors such as agriculture, the cost of sea-level rise, adverse impacts on health, non-market damages, as well as estimates of the potential costs of catastrophic damages (see below). The functions include damages from temperature change (T_{AT}), damages from and taken as a function of sea-level rise

(SLR), impacts of CO_2 fertilization which are a function of atmospheric concentrations of CO_2 *(* M_{AT}*).* The approximation equation in the second line of (3) reflects the fact that damages can be reasonably well approximated by a quadratic in temperature over the near term. Figure 2 shows the damage functions from three sources: the results of the Tol (2009) survey on damages, the IPCC assessment from the Third and Fourth Assessment Reports, and the damage function in the 2011 vintage of the DICE-RICE models. All are described as a function of global mean temperature increase.

Uncontrolled industrial CO_2 emissions in Equation (4) are given by a level of carbon intensity, $\sigma(t)$, times output. Actual emissions are then reduced by the emissions-reduction rate, $\mu(t)$. The carbon intensity is taken to be exogenous and is built up from emissions estimates of the twelve regions, whereas the emissions-reduction rate is the results of policies to reduce emissions in different regions.

$$(4) \quad E^j_{Ind}(t) = \sigma^j(t)[1 - \mu^j(t)]Y^j(t)$$

The geophysical equations link greenhouse-gas emissions to the carbon cycle, radiative forcings, and climate change. Equation (5) represents the equations of the carbon cycle for three reservoirs.

$$(5) \quad M_j(t) = \phi_{0j} E(t) + \sum_{i=1}^{3} \phi_{ij} M_i(t-1)$$

The parameters ϕ_{ij} represent the flow parameters between reservoirs. The term ϕ_{0j} is the fraction of anthropogenic emissions that go into reservoir *j*. Note that emissions flow into the atmosphere. Accumulations of GHGs lead to warming at the earth's surface through increases in radiative forcing. The relationship between GHG accumulations and increased radiative forcing is derived from empirical measurements and climate models, as shown in Equation (6).

$$(6) \quad F(t) = \eta\{log_2[M_{AT}(t) / M_{AT}(1750)]\} + F_{EX}(t)$$

F(t) is the change in total radiative forcings of greenhouse gases from anthropogenic sources such as CO_2, $F_{EX}(t)$ is exogenous forcings, and the first term is the forcings due to CO_2.

Forcings lead to warming according to a simplified two-level global climate model:

$$(7) \quad T_{AT}(t) = T_{AT}(t-1) + \xi_1\{F(t) - \xi_2 T_{AT}(t-1) - \xi_3[T_{AT}(t-1) - T_{LO}(t-1)]\}$$

$$(8) \quad T_{LO}(t) = T_{LO}(t-1) + \xi_4[T_{AT}(t-1) - T_{LO}(t-1)]$$

$T_{AT}(t)$ and $T_{LO}(t)$ represent respectively the mean surface temperature and the average temperature of the deep oceans.

Definition of SCC

We can now make a rigorous definition of the social cost of carbon. From these equations, we can solve for the social welfare function, W, in terms of the various exogenous and policy variables. We then define the social cost of carbon at time t, SCC(t):

$$(9) \quad SCC(t) = \frac{\partial W}{\partial E(t)} \Big/ \frac{\partial W}{\partial C(t)}$$

The numerator is the marginal impact of emissions on welfare, while the denominator is the marginal welfare value of a unit of aggregate consumption in period t. The ratio puts the impact of a unit of emissions in terms of t-period consumption as a numéraire. We do not put a regional superscript on consumption as they have the same units in each period under our normalization, although we will return to the regional issue below.

One of the most vexing issues in climate change is the potential for abrupt and catastrophic climate change (see National Research Council 2002, Oppenheimer 1998, Oppenheimer and Alley 2004). Estimates for the economic costs of such scenarios are included in the damage estimates in the RICE model, but the model does not build in a precise tipping point at a given temperature increase, because such a tipping point has not been reliably determined. The potential for unbounded expected value of marginal utilities discussed by Weitzman (2009) and elsewhere is also not incorporated given the speculative nature of the empirical estimates from those studies.

Estimates of the SCC in the RICE-2011 model

We have estimated the SCC in the RICE model for several alternative scenarios. The first is for “base parameters.” These are the ones used in the RICE-2011 standard model (as described in Nordhaus 2010 with updates for recent data on output and emissions). A second run is a “low discount” run to show the sensitivity to alternative discount rates; this run is motivated by earlier studies indicating that this parameter has the greatest impact on the SCC. The low discount run uses a pure rate of time preference (PRTP) of 1% per year rather than the 1.5% in the base run. A final run is a “near-zero discount rate" that can be used to compare with the estimates from the Stern Review (2007). This uses a PRSP of 0.1% per year.

The methodology for estimating the SCC is straightforward. We begin with a control run. The central case examined here is one with no controls on carbon emissions (the carbon price in all regions set to zero). We then perturb emissions by 1 million tons in a given year (2015, 2025, …). We calculate the change in the present value of utility scaled by consumption in the given year. The units are 2005 US international dollars per metric ton of carbon and are expressed in terms of consumption in the given year.

We also calculate the SCC by region. These estimates calculate the change in the present value of utility of that region scaled by consumption in the given year for that region. Because we use the Negishi methodology, the sum of the country-specific SCCs equals the global SCC. If we were to use other approaches, such as simply looking at output changes, the calculations would be different. (We discuss this point below.)

We begin by showing the real interest rate in the three scenarios, as this is the most important determining variable. Table 1 shows the estimates of the real interest rate by region and year for the US as well as two large developing countries, India and China. The real interest rates are the discount rate on consumption in the RICE model by region (calculated from the Ramsey equation). We also show the idealized real interest rate that would be produced by an equilibrium calculation of the Ramsey equation using the growth in per capita consumption and population for the 2005-2105 period for that region.[1] The Ramsey calculations are very close to the long-run real rates in the model.

An important aspect of the model is that real interest rates are relatively high in the short run (the next decade or so). This puts a constraint on the SCC because it implies that, even with low utility discounting, the SCC will be reduced because the first few decades will have a relatively high discount rate.

Table 2 shows the global SCC for the major cases. The central estimate is for the base parameters and no controls. The estimate is $42.68 per metric ton of carbon for the no-controls case and $40.11 for the case with optimal controls for the year 2015. (If we

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[1] The Ramsey equation is the equilibrium condition in an optimal growth model with constant growth in population and per capita consumption, without risk or taxes. In this equilibrium, the real interest rate *(r)* equals the pure rate of time preference *(ρ)* plus the rate of population growth *(n)* plus the rate of growth of per capita consumption *(g)* times the consumption elasticity of the utility function *(α)*. Using the notation of this study, this would imply that in the long run, $r = \rho + \alpha g + n$.

measure per ton of CO_2, these are $11.64 and $10.94, respectively.) The prices rise at 3½ % per year for the first decade, and slightly slower in subsequent decades. A first surprise is that the SCC does not differ markedly between the optimized and no-control case. The reason for this result is that the damage function is close to linear in the range between the two cases. In other words, the marginal damage in early period is only slightly affected by optimizing emissions.

The SCC is $138 per ton C for the low-discount rate run. The SCC here is much higher, approximately by a factor of three, compared to standard discounting. The reason is well-understood – that low discounting puts a higher weight on damages in the distant future. We also show the SCC associated with *Stern Review* discounting. For this run, we set the pure rate of social time preference to 0.1% per year and the elasticity of the marginal utility of consumption to 1. The real interest rates are markedly lower in the *Stern Review* run, as shown in Table 1, because the investment rate rises. The calculated SCC for the first period (2015) is again higher than the other runs, $288 per ton C in 2015. This is close to the estimated SCC from the *Stern Review.*

Table 3 shows the SCC by region and for all regions for three periods and the base parameters with standard discounting and low discounting. The SCC for the United States is slightly below 10 percent of the global total in all runs and periods. Note that this figure is below that of the US Regulatory Impact Analysis because that group used market exchange rates, MER (US Regulatory Impact Analysis 2010 and Greenstone et al. 2011). It is difficult to see any logic other than inertia for using the MER (a discussion of the two approaches is contained in Nordhaus 2007).

The highest SCC is for China, with a regional value one-fourth of the global total. China's high value arises from its very high growth of output, its large size, and its vulnerability to climate change. Russia has the lowest SCC, primarily because estimates indicate that it may actually benefit from modest amounts of climate change.

<u>The social cost of carbon in the context of the 2 °C target</u>

The current estimates are based on current RICE-model estimates of economic damages from climate change. As can be seen in Figure 2, the RICE model estimates are at the high end of damage estimates, so it seems unlikely that much higher estimates can be derived from more severe damage functions in the absence of catastrophic climate change. In an optimized framework, this damage function leads to a maximum temperature increase of 2.88 °C and an average temperature increase of 2.55 °C over the period 2050-2300. This increase is above the target set by climate negotiators of a maximum of 2 °C.

It will be useful to determine the SCC along a path that is consistent with the implicit damage function behind the internationally agreed target. The current agreement is known as the "Copenhagen Accord" (see UN 2009). The accord adopts a target of limiting the increase in global mean temperature, "recognizing the scientific view that the increase …should be below 2 degrees Celsius." There was no scientific document to support this statement, although the EU has developed such a target in the context of a cost-benefit analysis.

It will be useful to put the Copenhagen target in the context of the current study. One possible rationale for the Copenhagen target is that countries are using lower discount rates than in the RICE model. This approach has been taken in many discussions and is a potential interpretation. It appears to the present author to be inconsistent with investment decisions in most countries and to the structure of returns, as I have discussed for example in Nordhaus (2007a, 2008).

The approach I take in the present study is that the Copenhagen targets reflect a different damage function. More precisely, I assume that the 2 °C target reflects a cost-benefit optimum with a damage function that projects higher damages than that used in the RICE model.[2] This is implemented by increasing the first-order damage coefficient (the intercept in the damage function) in the RICE model for two different cost-benefit solutions. In the first, the cost-benefit optimum produces *maximum* temperature increases for the 2050-2250 period that 2 °C above the 1900 level. In the second, the cost-benefit optimum produces *average* temperature increases for the 2050-2250 period that 2 °C above the 1900 level. The rationale here is that the average might be more sensible than a rigid maximum target.

We then did a sequence of runs in which the damage coefficient was changed until the results of the cost-benefit optimum led to the maximum or average temperature increase as described in the last paragraph. Our estimates are that the damage coefficient must be approximately 2.7 times larger than the RICE base estimates to produce a 2 °C average target, and approximately 4 times larger to be consistent with a 2 °C maximum temperature.

Table 2 shows estimates of the SCC for the 2 °C cases. These are approximately 2 times larger than the base case for the average and 3 times the base case for the maximum target.

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[2] An alternative would be to use a higher discount rate, as with the Stern Review, but we prefer the higher damage interpretation as more consistent with the expressed gravity of concerns about climate change. If we take an optimal policy under the low-discount scenario, this would lead to an average temperature increase of close to 2 °C.

The conclusion here is as follows: Economic models may not incorporate all the concerns of scientists and policymakers about the costs of climate change. They may underestimate the damages because of intangible impacts or concerns about catastrophic outcomes. If we increase the damage function so that the economic optimum coincides with the 2 °C target, we find that the SCC rises sharply. It would rise by a factor of 2 to around $100 per ton C in 2015 if the goal was to keep the average temperature increase below 2 °C; and it would rise even more to $125 per ton C in 2015 if the goal was a hard maximum of 2 °C.

II. The Issue of Equity Weights

Background

An important issue in estimating the SCC is whether they should include "equity weights," which deals with the treatment of different levels of consumption across space and time. The idea is that we should weight damages to poor people more heavily than rich people.

One of the early advocates of equity weighting was James Mirrlees. His argument is worth quoting at length because it was intended as a general approach and not only to global warming investments:

> Let me now also urge that there are aspects of benefit-cost analysis which can with advantage allow for distributional objectives. The way in which this can best be done is by systematic application of welfare weighting. The objectives we are discussing can be expressed by means of a social welfare function, which assigns to all possible allocations of income to individuals a numerical measure of welfare. This takes a practical form when we consider small changes in the incomes of individuals, and measure the resulting change in welfare by assigning to each individual a welfare weight. Each person's income change is multiplied by his welfare weight, and the algebraic sum of all these products is the measure of welfare change. The simplest way to capture distributional objectives is to make the welfare weight a decreasing function of the individual's income. A system of weighting that appeals to me is the inverse square law, according to which the welfare weight is the inverse of the square of the individual's income. [3]

[3] Mirrlees, James A. (1978) "Social Benefit-Cost Analysis and the Distribution of Income," *World Development* 6(2): 131-138, quote from p. 134.

In the context of global warming, there is a substantial literature on the question, including prominently a substantial number of contributions by Richard Tol (1999, 2005, 2008), David Pearce (2003), Chris Hope and Philip Maul (1996), David Anthoff, Cameron Hepburn, and Richard S.J. Tol (2007), Anthoff and Tol (2011), and U.S. Working Group (2010). While the general view is that equity weighting is appropriate, the analytical basis and approaches differ widely.

There are two approaches to equity weights. The standard approach, which I label the "cross-sectional approach," applies equity weights to the distribution of consumption or income at a particular time. This approach was taken by Tol (1999), IPCC (1995), OECD (2006), and many other authors. For example, if the total damages in 2050 are X, this approach distributes X among different countries or individuals and applies a weighting or marginal utility function to the individual consumptions. Because utility functions are (almost always) concave, this will imply that the SCC with equity weights is (almost always) larger than the SCC without equity weights. I think this approach gives misleading answers.

A second approach, which I call the "intertemporal approach," uses the same methodology but applies it to consumption over both time and space. This approach has been utilized by David Anthoff, Cameron Hepburn, and Richard S.J. Tol (2007), who criticize the cross-sectional approach as wrong. Under this approach, the introduction of equity weights is a complicated picture because it introduces changing average consumption over time. As we will see below, in this case, the SCC with equity weighting can be either larger or smaller in the intertemporal approach than without equity weighting. The intertemporal approach is conceptually and philosophically more appropriate than the cross-sectional approach because it includes equity considerations over time as well as over space, and we follow this approach below.

Analytical background

The estimates provided in the prior section estimate the SCC using Negishi weights for different periods and regions. In non-technical terms, these are "utility weights" or ones that weight increments of consumption by the marginal utilities for each region using the utility time-discount factor.

It is important to understand how this procedure fits into the idea of equity weighting. The treatment of equity weights is conceptually very similar to the question of defining the social welfare function in our modeling. Under certain conditions, they are identical concepts. In utility-based models, such as the RICE model, we use a utility function to determine the choice of consumption over space and time. The utility function will generally reflect diminishing marginal utility of consumption, which reflects different weights on different levels of per capita consumption. So, a utility-based model explicitly contains equity weights. It is possible that the weights used in the utility function will differ from the weights that might be assumed for equity weighting, in which case we have a dilemma about how to interpret the results. But the first point to note is that a utility-based model such as the RICE model already contains equity weights.

We introduce equity weighting formally as follows: We have a vector of damages of n different countries or individuals and time periods, $\{D_1(t), \ldots, D_n(t)\}$, for $t = 0, \ldots, t, \ldots$. The countries have per capita consumptions of $\{c_1(t), \ldots, c_n(t)\}$. We assume a social welfare function in which the flow social evaluations (or the equity valuations) of consumption are $U[c_i(t),t]$. I introduce the time argument to indicate that the utility function may treat different time periods differently, but for this purpose I assume that individuals are treated identically at a given time. (The issue of sub-national inequality is not considered here. If the income distributions within countries are uniform and unchanging, then that consideration will not change the results.)

For simplicity, as with the SCC discussion above, we take small changes and use marginal valuations. We begin by calculating the difference of damages (that is, changes in consumption) in each period for each group, where these differences are denoted $\Delta D_i(t)$. We then calculate changes in welfare by weighting the difference of damages in each period for each group by its marginal utility, which yields:

$$(10) \qquad \Delta W = \sum_{t=1}^{T} \left\{ \sum_{i=1}^{n} U'[c_i(t),t] \Delta D_i(t) \right\}$$

the cross sectional approach, the disaggregation takes place in each period, whereas in the intertemporal approach all periods are used.

Many analysts assume that the utility function is constant elasticity. It is commonly called CRRA, which denotes constant relative risk aversion, but that is misleading in the current context. Here, it refers to constant relative aversion to inequality (CRAI), denoted by β, or the social evaluation of different levels of per capita consumption. In the risk context, risk aversion refers to the loss from the prospect of uncertain payoffs in different states of the world. Inequality aversion refers to the welfare loss from people having different levels of consumption. We will use the term CRAI to prevent confusion with risk aversion.

It will be helpful to indicate why the CRAI utility function is identical to assuming a certain degree of equity weighting. For simplicity, we can take the value of $\alpha = 1$, which yields logarithmic utility, or $U(c) = ln(c)$. Suppose we have a rich country or generation with a per capita consumption of 4 and a poor country or generation with a per capita consumption of 1. The marginal utility (MU) or valuation of consumption is $U'(c) = 1/c$. So the MU of the rich generation is 1 while that of the rich is ¼. This indicates that a unit of damages of the rich is valued at ¼th of the poor. This also shows why an output-based model would not include inequality aversion. In an output-based model, each country's consumption has equal weight, which implies that $\beta = 0$, and the equity weights are equal for all levels of consumption.

The CRAI utility or welfare function is $U(c) = c^{1-\beta} / (1-\beta)$, and marginal utility is $U'(c) = c^{-\beta}$. We also need to consider that the damages accrue over time, and that incomes change over time. We can apply a pure rate of social time preference (δ) to obtain the total welfare change, where the consumptions are now time-dated:

$$\Delta W = \sum_{t=1}^{T} \left\{ \sum_{i=1}^{n} c_i(t)^{-\beta} D_i(t)(1+\delta)^{-t} \right\} \quad (11)$$

Note that the RICE model uses certain values of time preference and consumption elasticity for model calibration to market data. In the RICE model, the time preference is denoted as ρ and the consumption elasticity is denoted as α. We use the parameters β as the elasticity and δ as the rate of time preference to distinguish the assumptions from the ones used in RICE model calibration. Governments might choose to override these market calibrations in making policy decisions involving the distribution of income over time and space, in which case $\alpha \neq \beta$ and $\delta \neq \rho$. Note that the individual and country decisions on investment and consumption in the RICE model are based on the RICE parameters, ρ and α.

We can apply the formula in (11) for different values of time preference and inequality aversion. Note that the standard calculation (without equity weighting) implicitly sets the coefficient $\beta = 0$, implying no inequality aversion. Further, the cross-sectional approach only applies the formula in (11) to corrections at a single time period.

The major question in the intertemporal approach is what good to select as the numéraire. The interpretation here is that we are considering the impact of greenhouse gas emissions today on future damages. In the context of the application of the SCC, we are considering investments today that will reduce emissions. Because we are considering mitigation investments at time 0, we use the average social marginal utility of consumption at time zero (the base period) as the appropriate numéraire. Two natural numéraires are "rich-country calibration" if the costs of emissions reductions are borne by rich countries; and "world calibration" if the costs of the emissions reductions are in all countries. There are other choices, but these would seem the most interesting normalizations to examine.

To understand the interpretation of the numéraire, assume that the emission reductions are undertaken by the rich countries in period 0. This means that the loss in welfare from emissions reductions would be weighted by the marginal utility of consumption of rich countries in the 0^{th} period. The reduced damages would accrue to many countries in many periods, and those would be weighted by the period-and-country marginal utilities.

Utility-based v. output based models

Before presenting the results, it is worth noting the difference between utility-based and output-based models. Some models have outputs as their metrics (goods and services, either as GDP or consumption). In these models, it is necessary to use a utility function and discount rate to do equity adjustment. Otherwise, we would just be adding up goods over time and space. Output measurement is the approach taken by the Interagency Group (US Regulatory Impact Analysis 2010, Greenstone et al. 2011). The reasoning was that emissions reductions also impose costs, and hence it would be necessary to consider the distribution of costs. The approach examined here addresses this concern.

A second class of models, of which RICE is an example, is utility-based. These models generate outputs, but they then evaluate them using a social welfare function. This means that they include welfare weights, or what are the equivalent of equity-weights, in the social welfare function. If the welfare weights in the model utility functions are the same as the equity weights, then the model will automatically provide the appropriate equity weights. Note also that output-based models are a special case of utility-based models, where the consumption elasticity or CRAI is $\beta = 0$. In this case, the equity weights are equal across space and time.

Estimates of the SCC

We use the same basic data for our discussion of equity weighting as the estimates for the SCC in the RICE model in section I. The first step is to calculate the impact of a unit of additional CO_2 emissions in the first period (2015). We then have an array of incremental damages in the future (in periods 2015,… 2305) for all regions (US, EU, India, China, …). This part of the calculation depends only on the basics of the baseline model. It is just a complicated modeling exercise to translate emissions into goods and services (or their aggregate) in each year.

The next step is to apply equation (11) using different parameters for β and δ, from which we calculate the equity-weighted SCC. The estimated SCCs are shown in Tables 4 and 5. Beginning with Table 4, this would be the standard calculation using most models where the damages are added up using all-country weights. The number in the box ($48/tC) is the estimate using the discount rate and elasticity from the base RICE-2011 model. It is slightly different from the results reported in Table 2 because the weights are slightly different.[4] Note that the SCC rises if either the inequality aversion falls or if the discount rate falls.

Table 5 shows the results with rich-country weights. Because per capita consumption in rich countries is roughly 3 times the world average, the marginal utility is much smaller, so the SCC with rich-country weights is also much larger. This can be seen looking at the case with β = 1 and δ = 0 (logarithmic utility and no discounting). In this case, the SCC ratio for rich-country to all-country normalization is a little larger than 3 ($3078/$937).

So the first and not terribly surprising result is that the SCC depends importantly on how we normalize the marginal utility of consumption. If we normalize by rich countries rather than all countries, the SCC can become substantially larger. How much larger depends upon the inequality aversion.

The next question is the impact of equity weighting on the SCC. We can also look at the *ratio of the SCC with and without equity weights* in Figures 3 and 4. Figure 3 shows all country weights. This uses weights in which the weights are determined by the weighted marginal utility of consumption today in all countries, where the weights are proportional to country shares in 2005 world GDP. The height of the bars shows the ratio of the SCC with equity weights to those without equity weights. Since no equity weights is the same as β = 0, we see that the bars are equal to 1 for β = 0. The horizontal axis shows different rates of time preference. The damages are summed through 2300.

The striking result here is that when we use intertemporal equity weights, equity weights reduce the SCC dramatically. For example, if we use logarithmic utility (β = 1),

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[4] There is a technical issue about the weights to use in combining countries. The RICE model determines the world rate of return by averaging the rates of return in different countries by their weights in the world capital stock. The results in Table 1 use GDP weights and normalize over the marginal utilities, which seems a more natural approach in the present context.

the SCC is between 10 and 30 percent of the unweighted SCC, with the lower number coming with the lower discount rate. The reason is straightforward: reduced damages accrue to future generations, who are projected to be richer than current generations. If planners are more inequality-averse, say with $\beta = 2$ as Mirrlees advocates in the quotation above, then the equity-weighted SCC becomes much smaller than the non-equity weighted. For the extreme case of high inequality aversion ($\beta = 2$) and 0 time preference, the equity-weighted SCC is only 1 percent of the non-equity-weighted.

An alternative is to assume that the numéraire is current rich countries – the U.S., Europe, Japan, and other high-income countries. This would be the way of introducing the SCC for the first round of the Kyoto Protocol. This case is shown in Figure 4. This case becomes more complicated and interesting. Almost all cases show the same phenomenon as in Figure 3, that equity-weighting lowers the SCC. But the difference is smaller than with all-country weighting. For all but the highest rate of time preference, equity-weighting reduces the SCC. For intermediate rates of time preference, the SCC is reduced by between 0 and 50 percent, while for the lowest time preference the reduction is 24 to 35 percent of the no-equity-weighted SCC.

So here is the second and surprising result: Equity weighting tends to reduce the SCC relative to no equity weighting. The extent of the reduction depends on the normalization and the parameters, but can be substantial.

What is the intuition behind this surprising second result? The result is a reflection of the (modeling) fact that the beneficiaries of reduced damages are richer than today's generation, who make the investments in slowing climate change. To take a concrete example, suppose that per capita consumption is growing at 2 percent per year, and that the damages on average accrue to people 70 years from now. At this growth rate, average consumption will be 4 times larger than today. If equity weights are based on logarithmic utility, then the weight on future consumption will be ¼th of current weights. With zero discounting this would produce an equity-weighted SCC one-fourth of the non-equity-weighted SCC. Putting the point differently, an investment by the average person today that pays off in 70 years will (in the models) accrue to people who are richer, and therefore equity-weighting will reduce the calculated utility payoff and the SCC.

The second case is more complicated because it assumes that the investments are made by rich people today and accrue to all countries in the future. To continue the example, suppose that rich countries are making the investments and are four times richer than the world average. Suppose further that the reduced damages accrue to all countries. Then the equity-weighted SCC will be equal to the non-equity-weighted SCC.

The only other factor to add to this discussion is the role of time discounting, which is also surprising. If there is no discounting, then the distant future will weigh very heavily in our calculations. The present calculation goes only through 2300. If we were to extend the time period with zero or very low discounting, the damages would accrue even more heavily to the rich future generations, and relative equity-weighted SCC would shrink even further (although the SCC itself would increase with longer time horizons).

One final point concerns the relative importance of discounting and equity weighting. If we examine Table 4, we see that for a central discount rate of 1% per year, the difference in the finding between the extremes of the equity weights is a factor of 43. Similarly, if we take the central consumption elasticity of 1, the difference in SCC across the extremes of the discount rate is 25. This indicates how differences in view on these normative parameters can introduce very large differences in estimates of the SCC.

The bottom line here is that equity weighting is a complicated affair. We cannot just look at the distribution of income of those who benefit from emissions reductions in a given period. We need also to look at where the investments are coming from. The results here suggest that, except in extreme cases of very high rates of time preference, long horizons, and high time discounting, the SCC will generally be reduced by equity-weighting. The reason is that benefits of the investments in reducing damages accrue to generations who are richer than today's. These may be valuable investments, but they are benefitting the rich.

III. Uncertainty of SCC

It is clear that there are major uncertainties about the value of the SCC. Some of these involve parameters like the discount rate, as shown in Table 2. In addition, there are geophysical and economic uncertainties, such as those involving the climate system, population growth, or future productivity growth.

We next present estimates of the uncertainty of the SCC using Monte Carlo techniques. For this purpose, we have developed estimates of 16 uncertain variables ranging from productivity growth to the temperature sensitivity coefficient. A list and the distributions are provided in the appendix. We then took 2000 runs for the Monte Carlo study. [5]

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[5] These are runs in the spirit of "learn, then act" and do not incorporate the need to act in the face of uncertainty. However, since most estimates are for a no-controls policy, the main proviso would be that runs with high realized SCC would trigger some kind of policy reaction.

The distribution of SCC for 2015 is shown in Figure 5. The mean SCC is $43.58 per ton C, which is 8 percent higher than the median of $40.51 per ton C. The median estimate of $40.51 per ton C is very close to the certainty equivalent estimate. (The difference between the $40.51 and the $40.11 is sampling error.)

The most important result of the uncertainty estimates is that the mean is slightly higher than the certainty equivalent. This is due to the non-linearity and interaction of the uncertain variables. There is an interaction effect among the uncertain variables so that two extreme high values produce algebraically higher numbers than the corresponding two extreme low values. For example, a two-sigma temperature and carbon cycle combination gives a SCC that is above the certainty equivalent by a larger amount than a negative two-sigma combination is below it.

However, the effect of the non-linearity is relatively small. This effect arises because of the relationship between damages and output growth. Even though there are several realizations that have high ratios of damages to output, these generally occur when consumption is high, and therefore the net output is still relatively high. We discuss this point further in the next section.

Treatment of Risk Aversion

Because of the large uncertainties, it is necessary to consider the interaction between the risks of climate change and the SCC. The standard approach is to consider the distribution of damages and then apply risk aversion to the distribution. This approach was taken in early studies by the present author and was used by the Stern Review. As we will discuss in this section, this procedure is generally not correct, and a treatment which integrates the climate uncertainties with the overall economic uncertainties should be used.

The issue here is whether we should weight the SCC higher for outcomes where climate change is at the high end. At first blush, the answer is obviously yes. High-climate-change scenarios – where temperature change is 4 or 5 or 6 °C and the potential for major-damage thresholds appears – would seem to be ones for which we would pay high insurance premiums.

On further reflection, the answer is not so obvious. The modern theory of risk and insurance holds that the risk premiums on different outcomes are determined by the correlation of a risk with consumption in different states of the world (see several chapters in Mehra 2008). This approach, known as the consumption-capital-asset pricing model (CCAPM), looks at the fundamental determinants of risk premiums in a world in which all contingencies are insurable and where there are insurance markets for all types of risk. A situation has adverse risk characteristics and requires a risk premium if the bad outcome occurs when we are relatively poor.

Therefore, to determine whether there is a significant risk premium that should be used to modify the SCC, we need to know whether high-SCC outcomes are situations in which we are relatively rich or relatively poor. Such a calculation requires a general-equilibrium model that generates the uncertain outcomes and provides the accompanying consumption level, which is just what the RICE and other utility-based models can do. Suppose that high SCC occurs only when we are rich and can therefore particularly well afford to bear the risks. In this case, we would generally not want to redistribute income from a low-income outcome to a high-income outcome by paying a large insurance premium to reduce risks in the high-income, high-climate outcome.

The analysis of the SCC under uncertainty can be developed as follows. Begin with the definition of the SCC at time t = 0 without uncertainty as follows. For this exposition, we omit population growth and regional differences.

$$SCC(0) = \frac{\left(\partial \left\{ \int_0^{\infty} U[c(v)] e^{-\rho v} dv \right\} / \partial E(0) \right)}{\partial U[c(0)] / \partial [c(0)]}$$

This equation is a formal statement of the definition of the SCC. Note that it requires putting the numerator (the impact of a unit of emissions on discounted utility) in terms of first-period consumption by dividing by the denominator (which is the marginal utility of first-period consumption).

Next assume that there is a continuum of states of the world, indexed with θ. We then want to calculate the risk-adjusted value of the SCC, which is denoted by *R[SCC(0)]*. It is derived as follows:

$$(12) \qquad R[SCC(0)] = E\left[\frac{\left(\partial\left\{\int_0^\infty U[c(v)]e^{-\rho v}dv\right\} / \partial E(0)\right)}{\partial U[c(0)] / \partial[c(0)]}\right]$$

$$= \int_\theta \left[\frac{\left(\partial\left\{\int_0^\infty U[c(v,\theta)]e^{-\rho v}dv\right\} / \partial E(0)\right)}{\partial U[c(0,\theta)] / \partial[c(0,\theta)]}\right] f(\theta)d\theta$$

In the RICE framework, because first period output is exogenous, the marginal utility of first-period consumption is a constant across different states of the world. This implies that we can take the denominator out of equation (12), which yields:

$$(13) \qquad R[SCC(0)] = \frac{1}{\partial U[c(0)] / \partial[c(0)]}\int_\theta \left(\partial\left\{\int_0^\infty U[c(v,\theta)]e^{-\rho v}dv\right\} / \partial E(0)\right) f(\theta)d\theta$$

$$= \int_\theta SCC(0,\theta)f(\theta)d\theta$$

In other words, in a framework such as the RICE model where the metric is discounted utility, the calculated SCC fully incorporates risk. This is analogous to the result above for equity weights, where the utility-based model already includes equity weights. This does not argue that these are the correct equity weights or rate of risk aversion, only that the effect is already included. So the risk adjusted SCC can be calculated at the expected value of the SCC. This needs to be adjusted for future values of the SCC to the extent that the marginal utility of consumption is not constant across states of the world, in which case we would use the more general formula in equation (12). For the RICE model runs, the differences in the marginal utility of consumption for the first three periods are extremely small, and we can therefore use the expected value formula in (13).

Note that this result does not imply that we can use the expected value of damages in the risk-adjusted calculations. The calculation presented here is a *utility-based* measure of consumption. If we use an *output-based* measure of output, we would need to introduce risk weights that are determined by the overall risk in a particular state of the world.

This leads to a second important point, which concerns the relationship between consumption risk and climate change. If we examine the relationship in the RICE-2011 model runs, we find that high-climate outcomes are *positively correlated* with consumption. This implies that high-climate outcomes are *negatively correlated* with the marginal utility of consumption (because of the declining marginal utility of consumption with increasing consumption). Those states in which the global temperature increase is particularly high are also ones in which we are on average richer in the future. This leads to the paradoxical result that there is actually a *negative* risk premium on high-climate-change outcomes. Figure 6 shows the plot of per capita consumption and temperature increase in the year 2205. The relationship is positive, indicating that high-temperature outcomes are ones with high economic outcomes. (We have omitted the top and bottom 1 percent of runs as outliers, but these are included in all calculations.)

The reason for this surprising result is parallel to the results for equity weighting. They can be explained using a simple example. Suppose that all damages came because more intense hurricanes flooded the beach houses of very rich people in states of the world where incomes were very high. The logic of the result is that we should not pay an insurance premium today (paid for by non-rich people today) to insure against floods of rich people's houses in the future.

Put differently, the major factor producing different climate outcomes in our uncertainty runs is differential technological change. In our estimates, the productivity uncertainty outweighs the uncertainties of the climate system and the damage function in determining the relationship between temperature change and consumption. We can see this point by examining the relationship between the marginal utility of consumption in 2205 and temperature increase in that year. The correlation is negative, which indicates that rapid climate change occurs when incomes are high. The more general proposition is that the discounted value of utility is positively correlated with temperature change. This result will clearly depend upon the model and the assumptions about the distribution of uncertainties; it should therefore be taken as suggestive rather than definitive. However, it does illustrate that the risk premium on climate change will depend upon the source of the uncertainty, not purely on the existence of uncertainty.

IV. Alternative Estimates

There have been many estimates of the SCC in different models. Those who would like to apply these to energy or climate policy face the daunting task of sorting through the different estimates and deciding which seem most appropriate. I discuss alternatives and compare them with the current estimates in this section.

Meta-analysis

Richard Tol has been the leading scholar who has surveyed and analyzed alternative estimates of the SCC. This is an extremely valuable effort and one that has helped analysts understand the issue. On occasion, the Tol results have been labeled a "meta-analysis," and others have also used this approach. The idea is to combine the different studies into a grand distribution of estimates.

While it is valuable to examine alternatives and the factors determining alternative estimates, it is misleading to call this a meta-analysis in the usual sense.[6] The basic idea is that there are several samples from a population, and those samples can be combined to estimate a parameter or other statistic more efficiently. We can understand the procedure intuitively in the context of a clinical experiment. Suppose there are several controlled experiments to test the effect of drugs, perhaps a group of anti-depressants.[7] To simplify, further assume that the samples are drawn from the same population and that all protocols are identical. This will then yield a series of observations from each of the studies. The effects of the drugs can be estimated, along with the associated standard errors. The studies can be combined into a "meta-analysis" by combining the observations in the different studies. In some cases, this can be done by combining the statistics (if those are sufficient statistics), and in other cases the data are pooled. The combined estimates provide more accurate estimates of the parameter of interest (here, the impact of a given dose of the drug) than the individual studies.

We can see from this description why the use of meta-analytical tools for combining estimates of the SCC is questionable. First, the different studies are not independent samples from some underlying distribution. Second, there is no clear mechanism by which the data are generated. Third, there is no sense in which there is a sample size applied to a given study. Perhaps most important is that the studies are very unlikely to

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[6] A useful reference for the social sciences is Larry V. Hedges and Ingram Olkin, *Statistical Methods for Meta-Analysis,* Academic Press, San Diego, 1985.

[7] Jay C. Fournier et al. (2010) is an interesting example.

be independently generated; that is to say, there is the difficulty of double counting models or methods.

I will examine these problems in turn. One problem is how to deal with multiple studies by the same author. Nordhaus or Nordhaus and co-authors have seven entries in the Tol data set. Tol or Tol and co-authors also have seven entries. These are different versions or vintages of the same class of model and are clearly not independent.

Another issue concerns studies based on other models, such as that by William Cline (1997). The Cline study used the DICE model and made some changes to parameters, primarily the discount rate. Interpreting this estimate is even more complicated than the multiple studies because it is in the nature of an argumentative article espousing a particular view on discounting. A similar difficulty is that posed by the *Stern Review.* The estimates for the Stern Review were developed in the same manner that the Cline (1997) estimates were prepared – using the PAGE model (and thus in a sense double counting the estimates from that model) and using an alternative set of assumptions.

Yet a third issue arises when a research synthesis includes surveys or meta-analyses. For example, Tol includes Clarkson and Deyes (2002), which is a review of earlier estimates. So the meta-analysis has triple-counted studies included in this review.

The main conclusion on the different meta-analyses is that these definitely do not meet the standard requirements for a statistical meta-analysis and should be treated with caution. They would be more accurately described as research syntheses or quantitative summaries of the literature that show some of the important factors driving the estimates.

Comparison of the current results with other studies

Although the compilations of studies do not meet the standards of statistical meta-analyses, they are very useful summaries of findings of different studies. Tol (2005) has added a useful further analysis which reflects many of the issues discussed above. He has conducted a regression analysis in which he analyzed the impact of alternative assumptions on the SCC. In a recent update (Anthoff, Hepburn, and Tol 2008), they conclude, that "estimates of the social cost of carbon are driven to a large extent by the choice of the discount rate and equity weights; and that the more pessimistic estimates have not been subject to peer review."

I have taken the Tol data set and grouped the studies by the assumed pure rate of time preference.[8] I have used boxplots to summarize the data. Figure 7 shows all studies with a pure rate of social time preference (PRSTP) from -2% to +8% per year, while Figure 8 focuses on the central ranges from 0% to 5% per year. While there is a great deal of variation within each box, it is clear that the major factor lying behind the wide divergence in SCCs is the assumption about discounting. The median for PRSTP less than 2% per year is $109, while the median for values above that is $39/tC.

We can go one step further and compare the present study with the Tol data base. If we convert the median estimate here to his metric (1995 SCC in $1995 discounted to 1995), the SCC is $14.63/tC. (For comparative purposes, this is $12.52/t CO_2 in 2011$). We used the logarithm of the median social cost of carbon to correct for heteroscedasticity. This raises the issue of how to treat negative or zero values of the SCC. Because omitting these values would bias the estimates, I set all the zero or negative at SCC = 0.1 to include them in the sample. If we include as determinants linear, quadratic, and cubic terms in the PRSTP along with a year effect, the current RICE-model estimates are 51 logarithmic percent above other studies with OLS. The estimate is 21 percent above the average of other studies using least average deviation estimates to remove outlier influence. This has no statistical interpretation but is seen as a useful data comparison technique.

Another analysis was undertaken by the US Working Group (US Regulatory Impact Analysis 2010, Greenstone et al 2011). This analysis was used for rulemaking purposes for the U.S. government. It uses three models and then adjusts them in an ad hoc manner. This study approaches the discount issue by assuming a discount rate on goods rather than starting with a PRSTP and deriving a discount rate on goods. Table 6 shows the results of that study using four different discount rates on goods. The results for 4% per year goods discounting are closest to the results presented here and is reasonably close to the RICE model estimates. It is difficult to interpret the findings of the Working Group because the discounting assumptions are not linked to underlying parameters and the assumptions are a hodge-podge of scenarios. In future work, it would be better to integrate the underlying assumptions.[9]

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[8] The Tol data set is at http://hdl.handle.net/1902.1/16336 and was downloaded on July 27, 2011.

[9] To illustrate the difficulty, consider the central issue of what to use for a discount rate. The Interagency Group used discount rates that were independent of the output and consumption growth rates. Additionally, the group generally used US rates of return on investment but then included global welfare and damage estimates.

An important legal question for rulemaking in a national context is whether to use the global or national SCC. The national SCCs for the RICE model are shown by the results shown in Table 3. The US SCC is about one-tenth of the global number. While the US working group recommended using the global SCC without much justification, this is a serious conceptual and potentially also a legal issue if the question comes before the US courts.

A summary of findings from other studies is that estimates are widely divergent. However, the major difference is caused by difference in the treatment of discounting, which is a controversial and unsettled question. The estimates provided here are consistent with other studies in the Tol data base conditional on the assumption about the pure rate of time preference.

V. Conclusion

The present study presents a new set of estimates of the social cost of carbon. The distinguishing features of the present modeling are the following: First, it includes estimates of major variables through the summer of 2011. Second, it is a general equilibrium approach in which important variables (such as the real interest rate, the economic growth rate, and climatic variables) are determined endogenously rather than as exogenous assumptions. Third, it includes a large number of uncertainties and is therefore able to include a large number of reinforcing or cancelling effects of uncertainty. Fourth, it includes equity weighting but allows different equity weights.

The most important results are as follows: First, the estimated social cost of carbon for the current time (2015) including uncertainty, equity weighting, and risk aversion is \$44 per ton of carbon (or \$12 per ton CO_2) in 2005 US international prices. Second, including uncertainty increases the expected value of the SCC by approximately 8 percent. Third, equity weighting generally tends to reduce the SCC. Fourth, the major open issue concerning the SCC continues to be the appropriate discount rate.

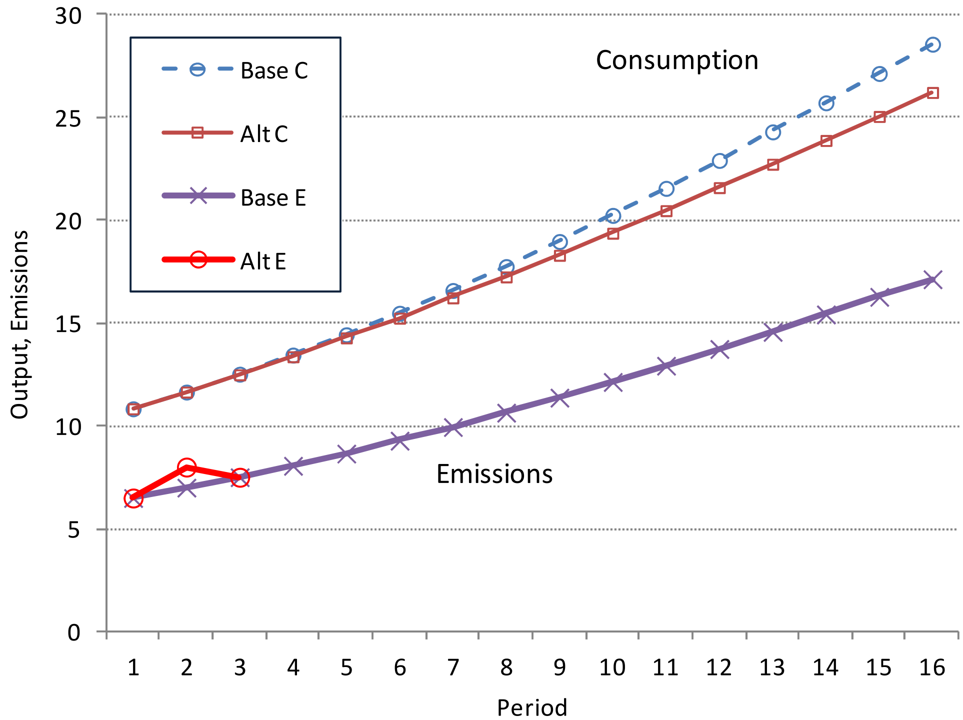

Figure 1. Illustration of calculation of social cost of carbon

In this example, emissions are increased by 1 unit in period 2. This leads to an alternative and lower path of economic welfare ("consumption"). The SCC is calculated as the present value of the difference in the consumption paths divided by the increment in emissions.

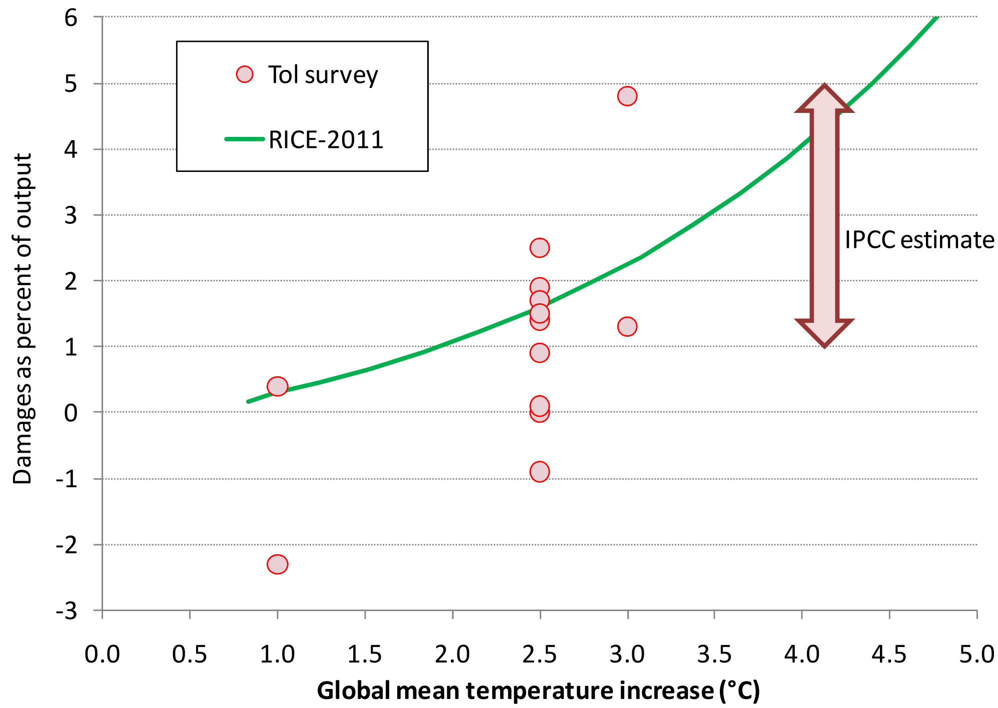

Figure 2. Estimates of the Impact of Global Warming on the Global Economy

This shows a compilation of studies of the aggregate impacts or damages of global warming for each level of temperature increase (dots from Tol 2009). The solid line is the estimate from the RICE-2011 model. The arrow is from IPCC Fourth Assessment, Impacts (2007).

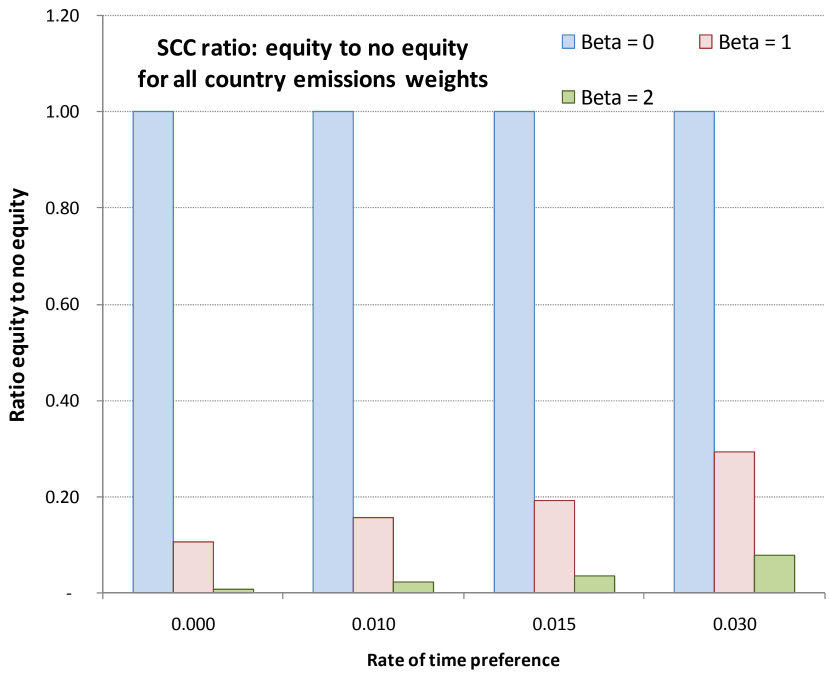

Figure 3. Ratio of SCC with to those without equity weighting where *all* countries' consumptions are used as numéraire.
"Beta" is the assumed elasticity of the utility function.

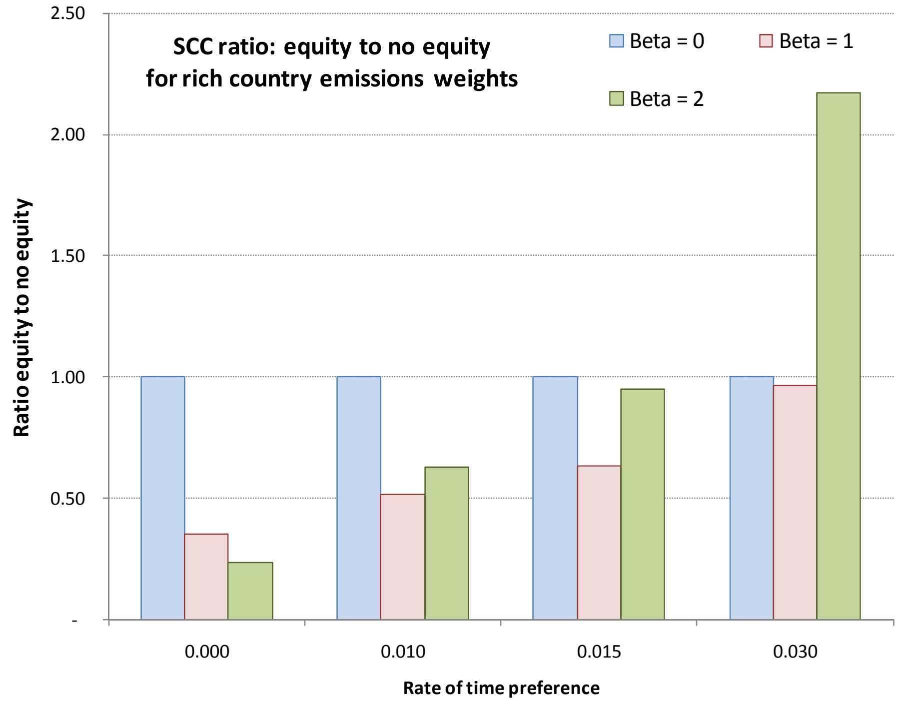

Figure 4. Ratio of SCC with to those without equity weighting where *rich* countries' consumptions are used as numéraire.
"Beta" is the assumed elasticity of the utility function.

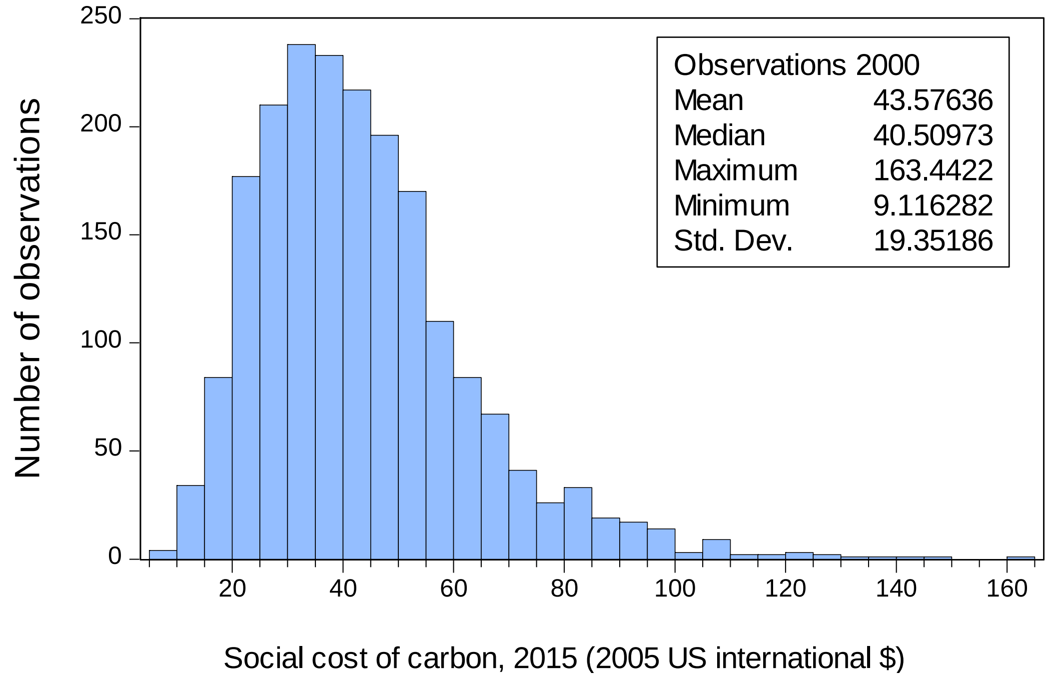

Figure 5. Distribution of the estimated SCC for 2015 in uncertainty runs

The figure shows the distribution of the SCC for 2015 for the uncertainty runs. The mean is slightly higher than the median and certainty equivalent because of non-linearity in the response function.

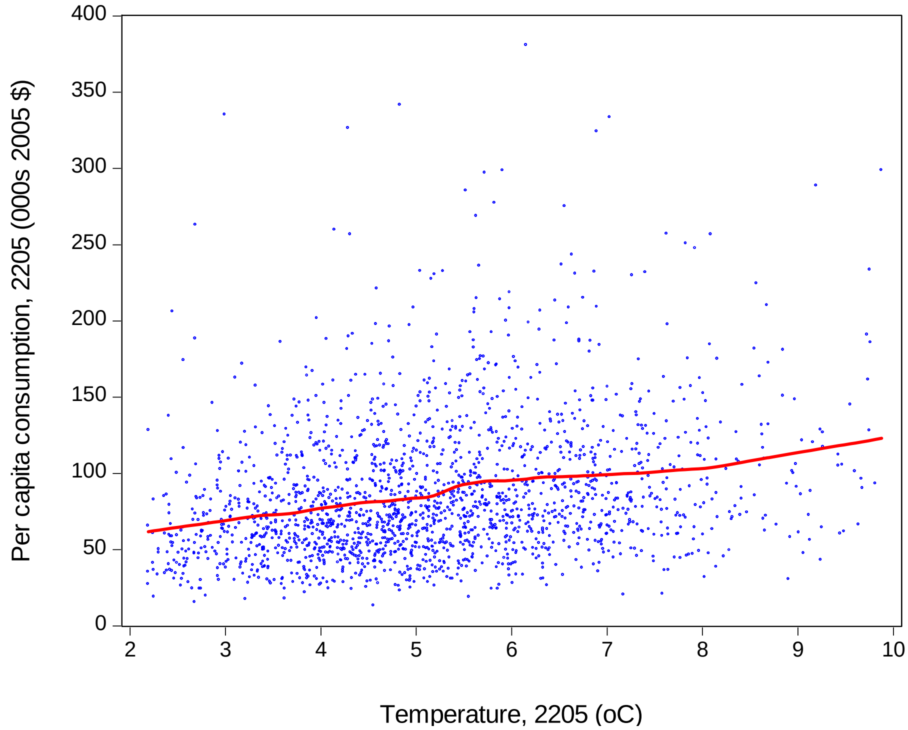

Figure 6. Scatter of temperature increase and consumption in 2205

High climate change outcomes are ones in which productivity and per capita consumption grow relatively rapidly. This implies that the risk premium on rapid climate change is negative rather than positive.

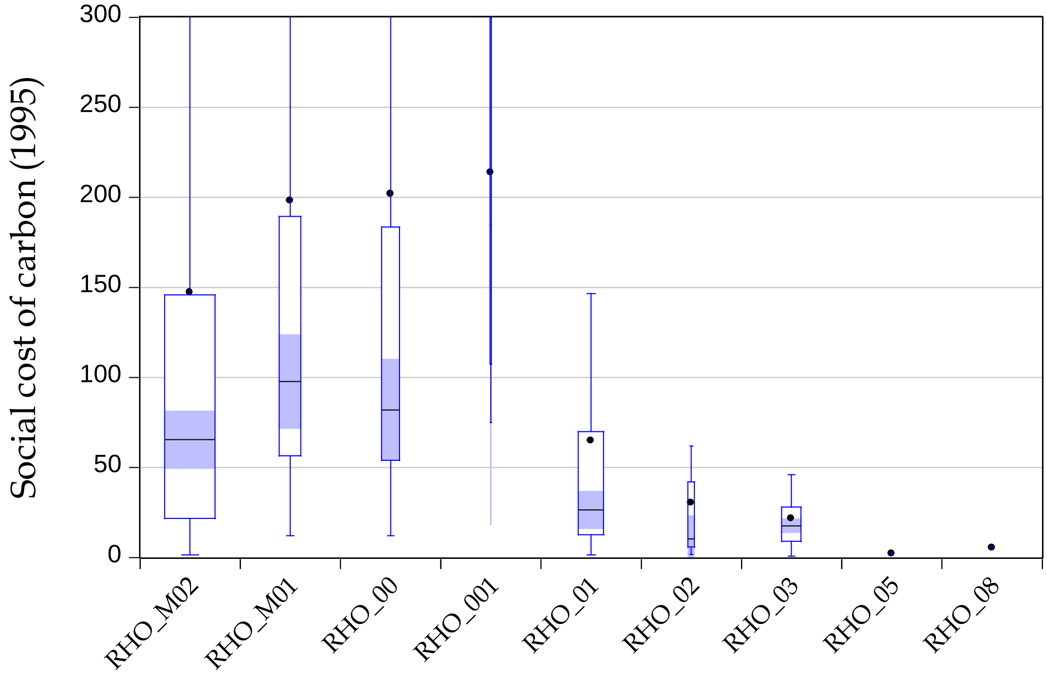

Figure 7. Boxplot of estimated social cost of carbon for different pure rates of time preference

The boxes show the inter-quartile range or (25, 75) percentile. The lower and upper whiskers are 1.5 times the inter-quartile ranges. The solid diamond is the mean. The shaded region is the estimated standard error of the median. A label of "rho_x" indicates that the social rate of time preference (SRTF) is equal to x% per year, with "M" indicating a negative number.

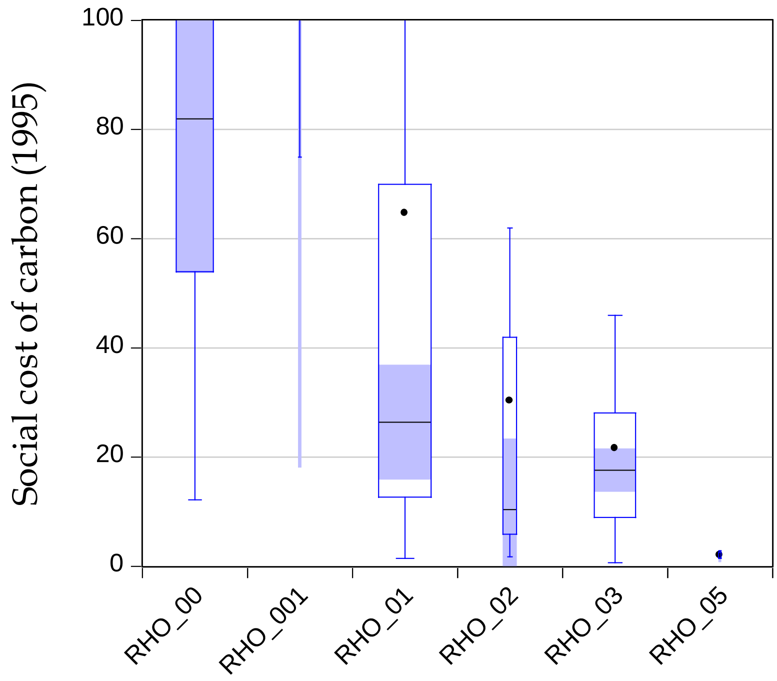

Figure 8. Boxplot of estimated social cost of carbon for central values of pure rates of time preference
For the meaning of the labels, see Figure 7.

Base run	2005	2005-2055	2005-2105	Ramsey model rate
US	4.1%	4.0%	3.3%	3.4%
China	10.8%	6.6%	3.0%	6.4%
India	10.3%	7.6%	4.1%	6.8%
World	5.9%	5.0%	4.2%	4.4%

Low discount rate run	2005	2005-2055	2005-2105	Ramsey model rate
US	2.8%	3.0%	2.3%	3.0%
China	7.2%	4.5%	1.8%	5.9%
India	7.1%	5.5%	2.8%	6.3%
World	4.0%	3.6%	3.0%	3.1%

Stern Review run	2005	2005-2055	2005-2105	Ramsey model rate
US	1.8%	2.1%	1.4%	1.9%
China	6.2%	3.5%	0.9%	4.9%
India	6.2%	4.5%	1.8%	5.1%
World	3.0%	2.6%	2.0%	2.1%

Table 1. Real interest rates by region and year: base, low, and Stern discount rate runs

The real interest rates are calculated as the real after-tax discount rate on consumption by region. The Ramsey model rate is calculated as the real interest rate from the Ramsey equation using population and per capita growth rates for the period 2005-2105.

	2015	2025	2035	2045	2055
Base parameters					
No controls	42.68	69.68	88.58	121.10	161.06
Optimal controls	40.11	65.32	82.51	111.91	147.41
Low discount run	138.21	221.43	246.01	333.95	442.91
Stern Review	288.35	364.21	487.67	627.47	759.01
2 degree damage					
Average	97.87	160.07	203.57	278.50	369.48
Maximum	124.86	202.84	254.48	343.97	450.42

Table 2. Global social cost of carbon by different assumptions

The social cost of carbon is measured in 2005 international US dollars. Countries' GDP are calculated using purchasing power parity exchange rates. To calculate the SCC per unit of CO_2, the figures should be divided by 3.67.

Base	2015	2025	2035
US	3.60	4.38	5.28
EU	4.11	5.20	6.29
Japan	0.78	0.95	1.11
Russia	0.51	0.79	0.95
Eurasia	0.48	0.87	1.24
China	10.40	23.92	31.70
India	7.98	16.91	26.03
Middle East	3.36	5.04	6.48
Africa	7.83	13.87	24.75
Latin America	2.60	3.97	5.41
OHI	1.37	1.77	2.06
Other developing	6.29	11.62	19.97
World	41.49	62.50	83.56

Low discount rate	2015	2025	2035
US	10.93	13.63	16.47
EU	7.73	9.91	12.00
Japan	2.07	2.58	3.07
Russia	1.25	1.85	2.24
Eurasia	1.22	2.00	2.72
China	28.94	57.03	74.05
India	20.11	37.17	53.13
Middle East	8.98	12.98	16.32
Africa	29.62	47.17	72.84
Latin America	6.87	10.00	13.11
OHI	4.17	5.43	6.44
Other developing	26.45	43.87	67.59
World	134.38	198.59	261.89

Table 3. Social cost of carbon by region, 2015-2035, base and low discount runs

The social cost of carbon is measured in 2005 international US dollars. Countries' GDP are calculated using purchasing power parity exchange rates. To calculate the SCC per unit of CO_2, the figures should be divided by 3.67.

SCC with all country normalization

Elasticity	Discount rate			
	0	0.01	0.015	0.03
0	8,752	1,305	619	126
1	937	206	119	37
1.5	257	75	**48**	19
2	76	30	22	10

Table 4. SCC with equity weights and all-country normalization

The table shows the estimated SCC for 2015 normalized by the marginal utility of consumption for all countries weighted by their GDPs. The social cost of carbon is measured in 2005 international US dollars. The number in the box (48) is the estimate from the RICE-2011 model using the model elasticity and discount rate. It differs from that in Table 2 because of differences in normalization for the first period.

SCC with all rich-country normalization

Elasticity	Discount rate			
	0	0.01	0.015	0.03
0	8,752	1,305	619	126
1	3,078	677	391	122
1.5	2,234	650	**421**	163
2	2,061	818	588	274

Table 5. SCC with equity weights and rich-country normalization

The table shows the estimated SCC for 2015 normalized by the marginal utility of consumption for rich countries weighted by their GDPs. The number in the box (421) is the estimate from the RICE-2011 model using the model elasticity and discount rate.

Year of discounting and emission	Social cost of carbon (2005 US $ per ton C)			
	Discount rate on goods			
	5.0%	4.0%	3.0%	2.5%
2015	20	41	83	134
2025	29	54	103	160

Table 6. Estimates of the social cost of carbon from US Interagency Working Group

Estimates are converted to 2005 prices using the US GDP price index. Source: US Regulatory Impact Analysis (2010), Table 4. The estimate for 4% is interpolated between the adjacent estimates using the geometric mean.

Appendix. Modeling details

The base run of the model is RICE-2011, available on the Internet at the author's web site at http://nordhaus.econ.yale.edu/. The model is an updated version of Nordhaus (2010). For reference purposes, the major changes are updating of the population data from the 2011 UN projections; updated output data from the World Bank and IMF; and updates of CO_2 emissions from CDIAC through 2007, with global total projected emissions to 2009. Country estimates for 2008-2009 for CO_2 emissions are from PBL. The model estimates are in "RICE11_052411_unc_v3a_base.xlsm."

Uncertainty runs

The uncertainty runs are generated from the base (no-controls) run. The SCC can be numerically calculated in three ways. First, we can estimate the optimal carbon tax by optimizing global welfare with respect to a carbon price. Second, we can do a numerical derivative by taking a small increment to emissions and calculating the effect on discounted utility. Third, we can take an analytical derivative by estimating the impact of emissions through the chain rule. These will differ slightly for computational reasons. In the deterministic case, the three approaches provide estimates of the SCC for 2015 of $40.28, $41.18, and $41.38, respectively.

The uncertainty model has 16 uncertain variables. For each of the 2000 random runs, they are selected randomly from the EXCEL random number generator. The SCC is calculated numerically as described in the text. The random runs are generated using a macro called "Monte" when operating in the "Results" sheet.

Table A-1 shows the random variables considered along with their distributions. Variables are taken to be either normal or log-normal.

As an example, the distribution of the temperature-sensitivity coefficient, which is one of the most studied of the uncertain variables, is assumed to be a log-normal distribution with a multiplicative standard deviation of 0.37. This leads to a (5^{th} %ile, 95^{th} %ile) of (1.62, 5.37) °C increase in global mean surface temperature per equilibrium CO_2 doubling. Figure A-1 shows the assumed empirical distribution. This can be compared with statistical estimates that range very widely as reported in the IPCC Fourth Assessment, Science (2007), pp. 721-722.

Equity weights

This appendix describes the calculations for the equity weights. We began with the latest version of the RICE-2011 model. We started with the baseline (no policy) run, and incremented emissions by 1 billion metric tons in 2015. We then calculated the change in damages by region and year from 2015 to 2305. We calculated the social marginal utility of consumption using the formula in the text for different rates of time preference and different elasticities. The numéraires were the weighted marginal utility of consumption in 2015, with weights being all countries' and rich countries' shares of GDP. The equity weights applied to damages were then these weights.

Table A-2 shows the raw results of the runs.

KEY PARAMETERS	Base value	Standard deviation of: Multiplicative uncertainty	Standard deviation of: Additive Uncertainty	Distribution
Rate of social time preference (% py)	0.0150			Fixed
Elasticity of MU of consumption (set)	1.5000			Fixed
Damage coefficient on temperature	0.0018			Fixed
Damage coefficient on temperature squared	0.0023	0.4643		Normal
Exponent on damages	2.0000			Fixed
Price backstop technology (2005 US 000 $ per tC)	1.2000	0.4000		Log-normal
Exponent of control cost function	2.8000			Fixed
Year acceleration backstop technology	2,250.0		50.0000	Normal
Maximum carbon resources (GtC)	6,000.0	0.2000		Log-normal
Equilibrium temperature increase for CO2 doubling	3.2000	0.3700		Log-normal
Decline rate TFP (per decade)	0.1000		0.0100	Normal
TFP convergence rate (per decade)	0.1000		0.0300	Normal
Long run growth rate (per year)	0.0033		0.0150	Normal
Decline rate sigma growth (per decade)	0.1000		0.0200	Normal
Trend sigma growth (per year)	-0.0025		0.0020	Normal
Uncertainty for frontier (US) TFP	0.0000		0.0050	Normal
Adjustment rates for SLR (multiplicative)	1.0000	0.5000		Log-normal
Random threshold temperature for melt SLR (m)	0.0000		0.5000	Normal
Population uncertainty (factor for 2200)	1.0000	0.2200		Log-normal
Carbon cycle adjustment coefficient	12.0000	0.3500		Log-normal
Convergence uncertainty	0.0000		0.2000	Normal

Table A-1. Assumptions for uncertain variables

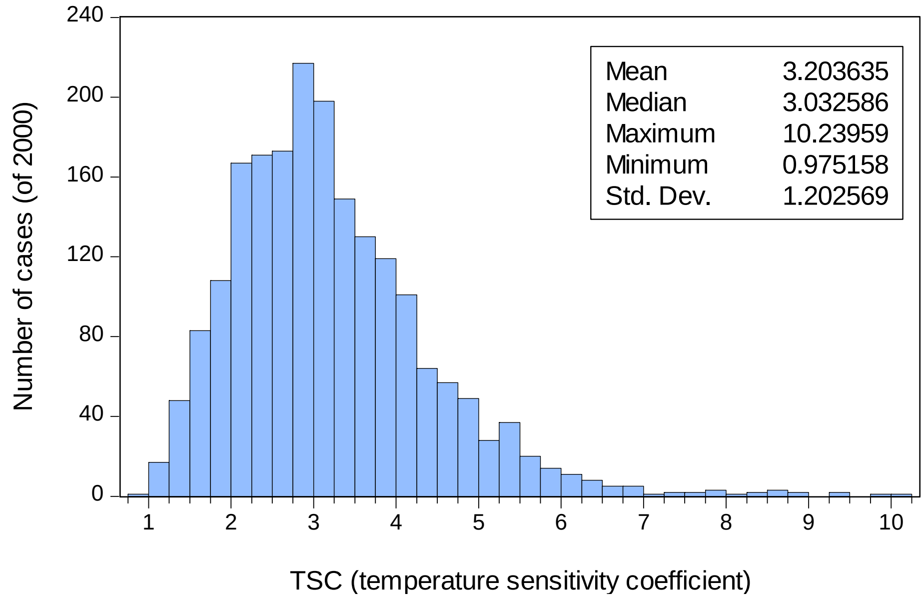

Figure A-1. Distribution of the TSC in uncertain runs

This figure shows the realizations of the TSC for the 2000 runs in the uncertainty estimates.

Cumulative weighted damages through given year for alternative beta and delta												
End year of												
summation		High	All		High	All		High	All		High	All
	2050	-12.68	-12.68	2050	-8.44	-8.44	2050	-6.92	-6.92	2050	-3.89	-3.89
	2100	-69.49	-69.49	2100	-33.49	-33.49	2100	-23.72	-23.72	2100	-9.17	-9.17
	2150	-173.98	-173.98	2150	-61.87	-61.87	2150	-38.70	-38.70	2150	-11.47	-11.47
	2200	-332.75	-332.75	2200	-88.22	-88.22	2200	-49.58	-49.58	2200	-12.28	-12.28
	2250	-558.90	-558.90	2250	-111.07	-111.07	2250	-56.96	-56.96	2250	-12.54	-12.54
	2300	-875.18	-875.18	2300	-130.51	-130.51	2300	-61.86	-61.86	2300	-12.63	-12.63
beta		0.00	0.00	beta	0.00	0.00	beta	0.00	0.00	beta	0.00	0.00
delta		0.00	0.00	delta	0.01	0.01	delta	0.02	0.02	delta	0.03	0.03
		High	All		High	All		High	All		High	All
	2050	-5.69	-18.69	2050	-3.86	-12.67	2050	-3.19	-10.48	2050	-1.85	-6.07
	2100	-19.55	-64.19	2100	-10.12	-33.21	2100	-7.44	-24.43	2100	-3.23	-10.61
	2150	-35.19	-115.56	2150	-14.44	-47.41	2150	-9.74	-31.98	2150	-3.59	-11.80
	2200	-52.11	-171.10	2200	-17.28	-56.72	2200	-10.92	-35.85	2200	-3.68	-12.09
	2250	-71.20	-233.80	2250	-19.22	-63.11	2250	-11.55	-37.92	2250	-3.70	-12.17
	2300	-93.75	-307.83	2300	-20.61	-67.69	2300	-11.90	-39.08	2300	-3.71	-12.19
beta		1.00	1.00	beta	1.00	1.00	beta	1.00	1.00	beta	1.00	1.00
delta		0.00	0.00	delta	0.01	0.01	delta	0.02	0.02	delta	0.03	0.03
		High	All									
	2050	-2.10	-56.84	2050	-1.47	-39.79	2050	-1.24	-33.47	2050	-0.75	-20.36
	2100	-4.15	-112.47	2100	-2.43	-65.76	2100	-1.90	-51.40	2100	-0.98	-26.47
	2150	-5.33	-144.43	2150	-2.76	-74.78	2150	-2.08	-56.24	2150	-1.01	-27.26
	2200	-6.17	-167.12	2200	-2.90	-78.63	2200	-2.14	-57.85	2200	-1.01	-27.38
	2250	-6.89	-186.74	2250	-2.98	-80.65	2250	-2.16	-58.51	2250	-1.01	-27.41
	2300	-7.61	-206.07	2300	-3.02	-81.85	2300	-2.17	-58.81	2300	-1.01	-27.41
beta		2.00	2.00	beta	2.00	2.00	beta	2.00	2.00	beta	2.00	2.00
delta		0.00	0.00	delta	0.01	0.01	delta	0.02	0.02	delta	0.03	0.03

Table A-2. Basic results for equity weighting in RICE-2011 model

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[Note that this is not intended to be a complete list of references on the subject. For a more complete list, see Tol 2008.]

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