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The Influence of the Specification of Climate Change Damages on the Social Cost of Carbon

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Abstract Drawing upon climate change damage functions previously proposed in the literature that we have calibrated to a common level of damages at 2.5 C, we examine the effect upon the social cost of carbon (SCC) of varying the specification of damages in a DICE-like integrated assessment model. In the absence of risk aversion, all of the SCC estimates but one agree within a factor of two. The effect of varying calibration damages is mildly sublinear. With a moderate level of risk aversion included, however, the differences among estimates grow greatly. By combining elements of different damage specifications and roughly taking into account uncertainty in calibration, we have constructed a composite damage function that attempts to approximate the range of uncertainty in climate change damages. In the absence of risk aversion, SCC values calculated with this function are in agreement with the standard quadratic DICE damage function; with a coefficient of relative risk aversion of 1.4, this damage function yields SCC values more than triple those of the standard function.

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1 Introduction

The social cost of carbon (SCC) is a monetized estimate of the change in social welfare that results from a marginal change in carbon dioxide (CO_2) emissions. Its evaluation requires an integrated assessment model (IAM) that couples together a global economic model and a model of the physical climate system. A core component of this coupling is a specification of damages that translates physical climate outcomes into effects on human welfare.

Ideally, damage specifications should be as comprehensive as possible and consistent the best available results from detailed impact, adaptation and vulnerabilities assessments. In the context of Monte Carlo simulations to estimate the SCC, they should also give meaningful results in low-probability, high-impact states of the world. The first pair of objectives is addressed through the calibration of damages within an IAM; the last objective is addressed through the choice of functional forms used to extrapolate damages beyond the calibration range.

The IAM DICE (Nordhaus and Boyer, 2000; Nordhaus, 2007), for example, is calibrated against estimates of damages at 2.5°C warming to agriculture (Darwin et al., 1995), coastal infrastructure (Yohe and Schlesinger, 1998), and health (Murray et al., 1996). It also includes ad hoc estimates of impacts on energy demand, ecosystems, and settlements (Nordhaus, 2007), as well as estimates based on an expert elicitation study of expected damages resulting from potential climate catastrophes (Nordhaus, 1994). In total, DICE estimates non-catastrophic damages equal to 0.6% of GDP and expected catastrophic damages equal to 1.2% of GDP at 2.5°C warming (Nordhaus, 2007). Damages are extrapolated beyond the 2.5°C calibration point by assuming an approximately quadratic relationship between temperature and fraction of GDP lost.

As another example, the IAM FUND (Anthoff and Tol, 2010; Tol, 2002) includes sector- and region-specific damage functions for agriculture (calibrated against five computable general equilibrium model evaluations published between 1992 and 1996), forestry (calibrated against Perez-Garcia et al., 1997, and Sohngen et al., 2001), water resources and energy consumption (calibrated against Downing et al., 1995, 1996), sea level rise (calibrated primarily against Fankhauser, 1995, for protection costs and Kattenberg et al., 1995, for sea level rise projections), the "warm glow" effect of ecosystem loss (Tol, 2002), diarrhea (calibrated against World Health Organization data), vector-borne diseases (calibrated against four studies from 1995-1997), cardiovascular disease (calibrated against World Health Organization data), and tropical and extratropical storm damage (calibrated against a World Meteorological Organization statement and Toya and Skidmore, 2007). These damages are functions of a combination of temperature, rate of temperature change, CO_2 concentration and adaptive capacity (indexed by wealth). For typical scenarios, they total about 0.9% to 1.6% of GDP at 2.5°C warming (Warren et al., 2006). (Note that FUND does not include potential catastrophic impacts.) The functional form used to extrapolate damages to higher temperatures varies between sectors.

The Intergovernmental Panel on Climate Change's Fourth Assessment Report notes that "on balance, the current generation of aggregate estimates in the literature is more likely than not to understate the actual costs of climate change" (Schneider et al., 2007). Consistent with this observation, the U.S. government's recent SCC analysis (Interagency Working Group on the Social Cost of Carbon, United States Government, 2010) noted the incomplete treatment of non-catastrophic damages, potential catastrophic damages, inter-sectoral interactions, and inter-regional interactions in the cost-benefit IAMs used for SCC estimation. These omissions likely all serve to lower damage projections. The U.S. government analysis also noted that adaptation is obscurely treated in some of the IAMs, which could either raise or lower damage projections, depending on the implicit assumptions. (See Kopp and Mignone, 2011, for further discussion.)

Uncertainty arises both in calibration and extrapolation of damages, as well as elsewhere in the IAM (e.g., in baseline socio-economic projections and in the physical climate model). The more comprehensively uncertainty is taken into account in the estimation of the SCC, the more sensitive the final values will be to the level of risk aversion. The U.S. government analysis assumed zero risk aversion, while different versions of DICE use a coefficient of relative risk aversion of either 2.0 or 1.5. (See Kopp and Mignone, 2011, for further discussion.)

In this paper, we use an implementation of DICE to evaluate the sensitivity of SCC estimates to the calibration and extrapolation of damages. We first review a range of alternate functional forms for DICE-like models that have been employed in the peer-reviewed literature. Next, we consider the effect on SCC estimates of substituting these functional forms for the default DICE quadratic damage function at three different levels of risk aversion and two different emissions scenarios, while keeping damages at the 2.5°C calibration point constant. We then return to examine the effects of changes in expected damages at the calibration point.

2 Taxonomy of damage specifications

The damage specifications that appear in peer-reviewed literature can be characterized based on a number of factors. Most represent damages as functions of temperature increase over preindustrial levels, while others take into account additional climate parameters, such as rate of warming or absolute CO_2 concentration. Rate terms reflect damages to which society can adapt when warming slows, while certain biogeochemical impacts (notably, CO_2 fertilization and ocean acidification) are controlled by concentration rather than level of warming. The damage

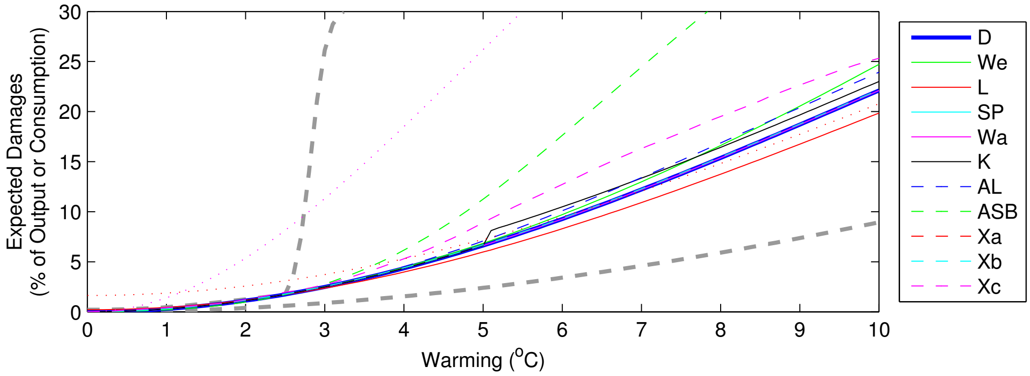

Figure 1: Expected climate damages for different damage functions, calibrated such that they all agree with the default DICE damage function for 2.5°C warming. Damage functions are defined in Table 1. Rate of temperature increase is set to 0.3°C/decade and level of wealth is set to its initial value. Dotted lines show L (red) and Wa (magenta) at 0.6°C/decade and five times initial wealth. Heavy dashed grey lines indicates the lowest 5th percentile value and the highest 95th percentile value across all damage functions, excluding Xc.

functions are typically power functions of these parameters and can be bounded through a rational or exponential mapping. Some damage functions attempt to treat uncertain catastrophic damages in an explicit, stochastic fashion, whereas others fold their expected impacts into deterministic terms. IAMs can also take into account damages to environmental goods that do not become more abundant with increasing material wealth, either by including within the damage function terms that increase with total wealth, or through a modification of the production or utility functions that effectively achieves the same end. The damages can be applied to output, to utility, and/or to capital.

The damage functions evaluated in this study are summarized in Table 1 and discussed below. Table 2 provides parallel descriptors for damage specifications that appear in cost-benefit IAMs other than DICE. Figures 1 and 2 show damages as a function of temperature with different specifications; figures 3 and 4 provide an alternate perspective, showing the implications for consumption in the reference scenario of different damage functions.

2.1 Polynomial functions of temperature

As noted in the introduction, climate damages in DICE are an approximately quadratic function of global average temperature increase over preindustrial levels ($D(T) = aT^b$, $b = 2$). Early versions of DICE (e.g., Nordhaus, 1992) used D directly as their damage function. Later versions (e.g., Nordhaus and Boyer, 2000) bound damage at 100% of GDP by the rational mapping $\Omega(D) = 1 - 1/(1 + D)$. Weitzman (2009) suggests bounding damages using an exponential mapping

Table 1: Key characteristics of damage functions assessed

	Source	Function of	Functional form	Uncertainty	Upper bound	Applied to
D	DICE 2007	Temperature	Quadratic.	No	Rational	Output
We	Weitzman (2009)	Temperature	Quadratic	No	Exponential	Output
L	Lempert et al. (2000)	Temperature, Rate	Quadratic in temperature; Cubic in rate	No	Rational	Output
SP	Sterner and Persson (2008)	Temperature, Wealth	Quadratic	No	Rational	Output, Utility.
Wa	Weitzman (2010)	Temperature, Wealth	Quadratic	No	Rational	Utility.
K	Keller et al. (2004)	Temperature	Quadratic.	Uncertain threshold damages	Rational	Output
AL	Azar and Lindgren (2003)	Temperature.	Quadratic; Quartic for catastrophic.	Uncertain functional form	Rational	Output
ASB	Ackerman et al. (2010)	Temperature	Power, exponent varying from 1 to 5.	Exponent	Rational	Output
Xa	This study	Temperature	Quadratic	Uncertain threshold damages	Rational	Output
Xb	This study	Temperature	Quadratic	Uncertain threshold damages	Rational	Capital, Output, Utility
Xc	This study	Temperature	Power (log-normally distributed exponent)	Exponent and uncertain threshold damages	Rational	Capital, Output, Utility

Table 2: Key characteristics of damages in other major cost-benefit IAMs

IAM	**Function of**	**Functional form**	**Uncertainty**	**Upper bound**	**Applied to**
FUND	Temperature, Rate, CO_2 concentration, Wealth	Varies by sector	No	By sector	Output
PAGE	Temperature	Power function, uncertain exponent (1 to 3)	Exponent and uncertain threshold damages	No	Output
MERGE	Temperature	Quadratic	No	No	Output
CETA-M	Rate	Cubic in rate	No	No	Output

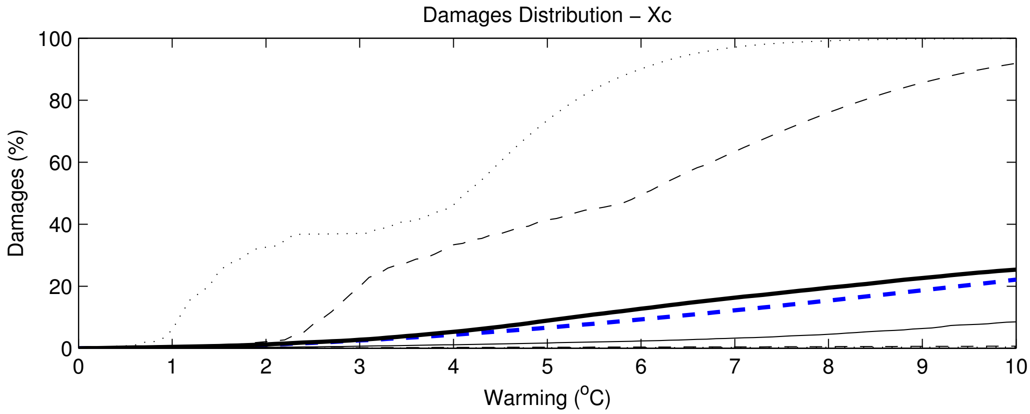

Figure 2: Distribution of damages for Xc. Heavy black line indicates expected damages, while the thin line indicates median damages, dashes lines indicates the 5th and 95th percentile, and dotted lines the 1st and 99th percentiles. The jaggedness of the dotted line reflects numerical noise. The blue line, for reference, indicates the standard DICE damage function.

($\Omega(D) = 1 - e^{-D}$) rather than a rational mapping. This mapping matches the standard DICE mapping at low-to-moderate temperatures but approaches 100% of GDP more rapidly at higher temperatures. With the exception of damage function We, we apply the standard DICE rational mapping for all the damage functions we model.

A number of IAMs adopt similar polynomial forms to DICE. MERGE (Manne et al., 1995) adopts the DICE quadratic function for market damages and applies a separate willingness to pay (WTP) function for non-market damages. PAGE (Hope, 2006) models economic, non-economic, and catastrophic ("discontinuity") damages separately for eight geographic regions, all as power functions in a form also similar to DICE, but with the exponent treated as uncertain, ranging from 1 to 3, instead of being fixed at 2 as in DICE.

Ackerman et al. (2010) introduces greater uncertainty in the damages exponent by modifying DICE, treating b as a random variable with a triangular distribution with mode 2, minimum 1, and maximum 5. Along similar lines, Mastrandrea and Schneider (2001) adjust b through iteration with a simple model of the Atlantic Meridional Overturning Circulation (AMOC) to incorporate the expected damages associated with decline or collapse of AMOC.

2.2 Polynomial functions of temperature and rate

A number of functions are dependent on the trajectory of temperature increase. Damages in CETA (Peck and Teisberg, 1992), for instance, depend on the decadal rate of temperature change. Lempert et al. (2000) develop a damage function

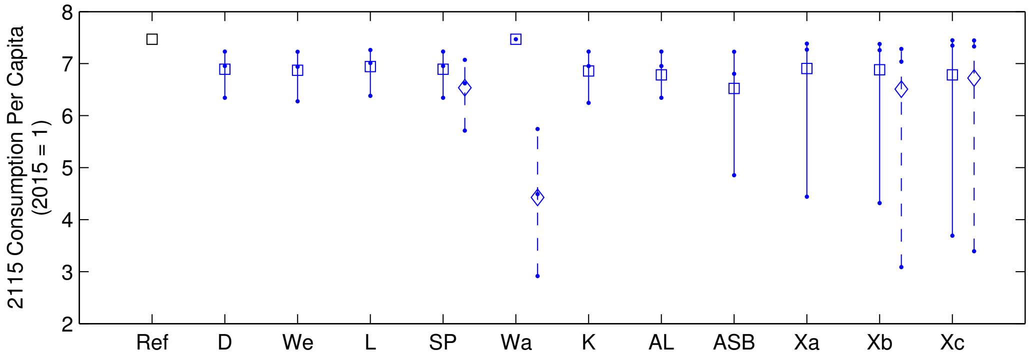

Figure 3: Consumption per capita in 2115 for the reference scenario with different damage functions. Squares indicate expected changes, while dots connected by lines indicates 5th, 50th, and 95th percentiles. When a modified utility function is used, diamonds and dashed lines indicate effective consumption per capita. In the absence of climate damages, per capita consumption in 2115 is 7.5 times per capita consumption in 2015.

intended to capture the impacts of climate variability. Their function includes a term with the five-year running average of temperature for variability to which society and ecosystems can adapt on the timescale of several years, and another term with 30-year running averages for variability to which society and ecosystems adapt over longer timescales:

$$D(t) = a_1 \overline{T}_5^{b_1} + a_2(T - \overline{T}_5)^{b_2} + a_3(T - \overline{T}_{30})^{b_3} \tag{1}$$

where $\overline{T}_5$ and $\overline{T}_{30}$ are five- and thirty-year running averages of temperature. (Since our model has ten-year time steps, $T = \overline{T}_5$, so we set a_2 to zero in our implementation of this function.)

2.3 Polynomial functions of temperature and wealth

Damage functions are typically expressed as a fractional loss of output, but some work has explored damage specifications in which effective damages at a given temperature increase more rapidly than output. The intent with these specifications is to represent damages to environmental goods for which material goods are imperfectly substitutable.

Sterner and Persson (2008) model these imperfectly substitutable goods directly. They employ a utility function for a representative agent that is dependent upon both material consumption and consumption of ecological goods. The former term grows with wealth; the latter term does not, so the relative value of ecological goods increases as society grows wealthier. Effectively, their model can be viewed

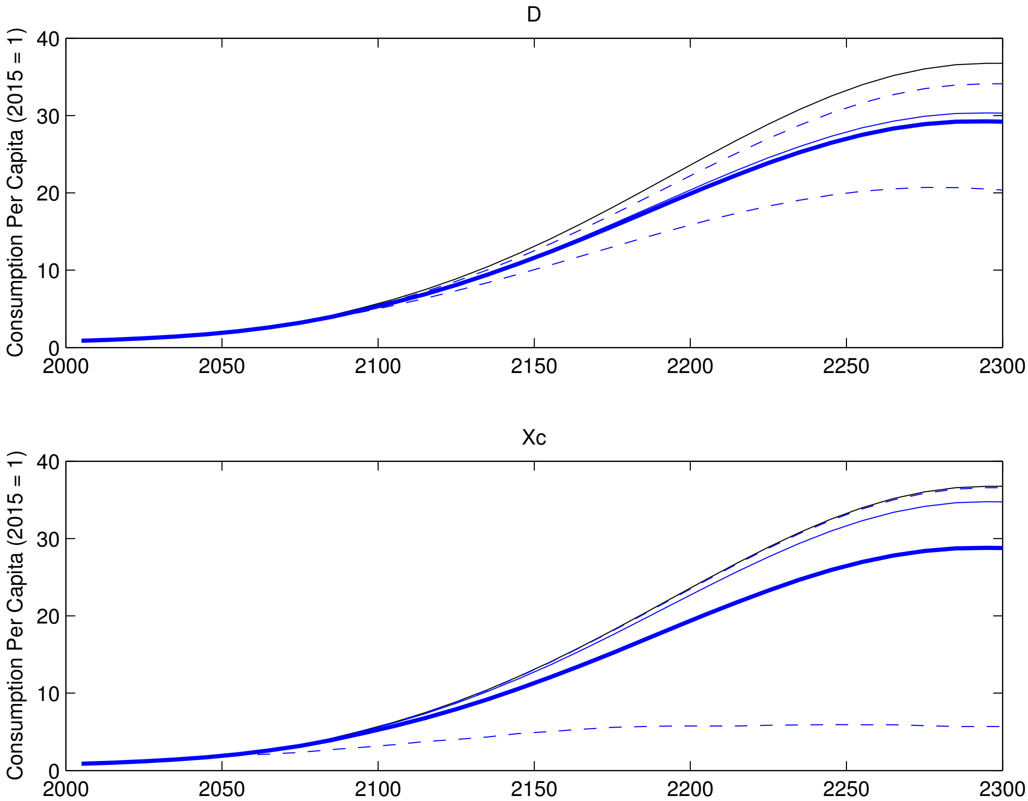

Figure 4: Changes in consumption per capita for damage functions D (top) and Xc (bottom). Black line indicates the reference path. Heavy line represents expected values, light solid line indicates median values, and dashed lines indicate 5th and 95th percentiles.

as substituting in the utility function effective consumption per caption C_{eff} for the standard material consumption per capita C:

$$C_{\text{eff}} = [(1-\gamma)C^{1-1/\sigma} + \gamma E^{1-1/\sigma}]^{\sigma/(\sigma-1)} \tag{2}$$

where E is the per capita consumption of ecological goods, γ is the fraction of utility accounted for by consumption of ecological goods, and σ is the elasticity of substitution between material and ecological goods. Just like output, E decreases with warming: $E = E_0/(1+D(T))$.

Weitzman (2010) presents an “additive” specification of damages, which he contrasts with the standard “multiplicative” specification. (The terminology derives from the appearance of the utility function with the two different specifications when the coefficient of relative risk aversion is equal to 2.) The additive specification is equivalent to making relative damages a function of wealth as well as temperature: $D(C,T) = aCT^b$. Weitzman argues that this alternative form is as plausible as its standard “multiplicative” equivalent on a priori grounds. He also shows that shows that the Sterner-Persson utility function possesses the same properties as a utility function with both additive and multiplicative damage terms.

Note that – due to the relative price effects Sterner and Persson (2008) discuss – the introduction of multiple, non-substitutible utility-enhancing goods has important implications for SCC calculations. The SCC is defined as the ratio of the change in expected welfare from a unit of emissions to the change in expected welfare from a unit of material consumption in the period of emissions. If E is declining over time – or even increasing slower than C – the relative value of a unit of material consumption is declining over time. This effect will appear in the denominator of the SCC, but it will appear more strongly in the numerator, where a stream of damages is being inflicted on a world less wealthy (in utility terms) than a world where C and E were perfectly substitutable. For values of risk aversion less than one, the net effect will be to decrease the social cost of carbon. In the calculations below where we employ a Sterner-Persson utility function, we therefore also present results calculated in terms of equivalent first-period material consumption: essentially, converting damages from current dollars to constant dollars. In constant dollars, incorporating an imperfectly substitutable, non-increasing good will increase the SCC. The conversion to constant dollars is given by:

$$C_{\text{equiv}} = \left(\frac{C_{\text{eff}}^{1-1/\sigma} - \gamma E_0^{1-1/\sigma}}{1-\gamma} \right)^{\sigma/(\sigma-1)} \tag{3}$$

where E_0 is equal to first period consumption of ecological goods.

As noted in the introduction, many of the damage functions in FUND also include wealth as a term (Anthoff and Tol, 2010), in order to reflect greater adaptive capacity in wealthier societies. Damages are modulated by terms such as $(y_0/y)^{\eta}$, where y is per capita GDP, y_0 is per capita GDP in a reference year, and η is between 0 and 1.

2.4 Uncertainty in functional form

Several damages specifications use uncertainty in functional form to represent more explicitly impacts from low-probability catastrophic events. For example, PAGE (Hope, 2006) allows for a discontinuity that causes damages equal to 5-20% of GDP. The probability of such a discontinuity increases at a linear rate with increasing temperature. Keller et al. (2004) model damages from the collapse of the AMOC, assumed to vary uniformly between 0 and 3 percent of global GDP, by adding a term for damages above a certain threshold.

Other modelers represent states of the world experience catastrophic damages with higher values for the exponent b in the damage function. Azar and Lindgren (2003) model two uncertain future states of the world: a high-probability state in which damages follow the quadratic form of DICE, and a low-probability but

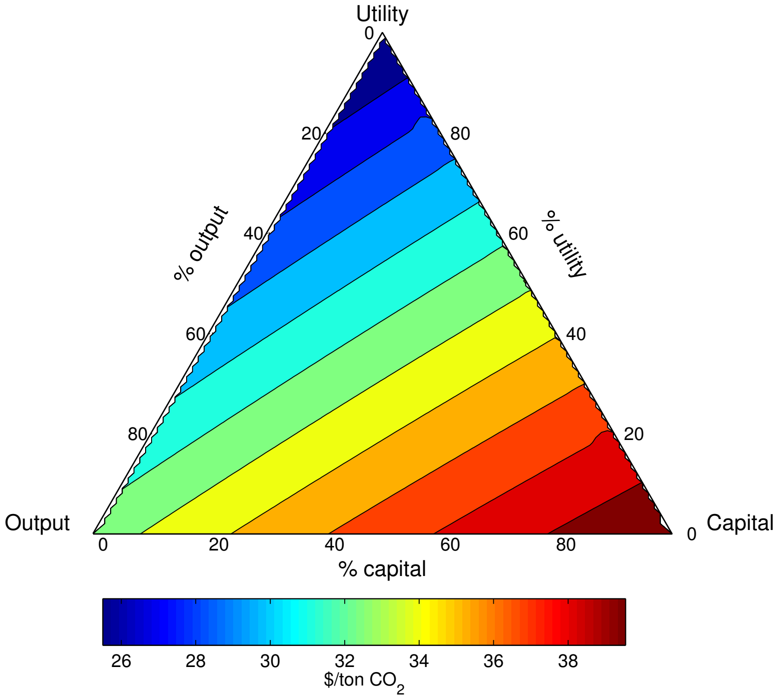

Figure 5: 2015 social cost of carbon, calculated at a flat 3% discount rate off of the reference scenario, using the standard DICE damage function applied in different proportions to capital, output, and utility. Most models apply damages strictly to output (bottom left corner). Pure capital damages and pure utility damages are shown in the bottom right corner and the top, respectively

catastrophic state in which damages are a quartic function of global average surface temperature change. Similarly, as mentioned previously, Ackerman et al. (2010) treat the exponent b of temperature in the damage function as uncertain; higher values of b cause damages to increase more rapidly with temperature and represent states of the world more subject to catastrophic climate change.

2.5 The nature of damages: Utility, output, and capital

In principle, damages from climate change can negatively impact three different terms in an economic model: utility (or effective consumption), output, and capital. Damages to utility represent negative impacts to the ability of individuals to benefit from material consumption; damages to output represent negative impacts on the ability to make productive use of capital; and damages to capital are simply that.

Even if calibrated so that the immediate impact on utility is the same, damages to utility, output, and capital have moderately different long-term implications. Damages to utility impact well-being but not the growth of the material economy. Damages to output leave current capital untouched but reduce investment and therefore future capital and output. Damages to capital will produce the same investment reduction as damages to output, while also impacting current capital. Consider the effect of a short but very severe shock to each of these factors: a severe shock to utility will temporarily make people very unhappy; a severe shock to output will cause a recoverable depression; and a severe shock to capital will require a protracted period of rebuilding. For the same damage function, the SCC will therefore be higher the greater the proportion of damages accruing to capital, and lower the greater the proportion accruing to utility (Figure 5).

Most of the damage specifications in the literature impact output, while Weitzman (2010) simplifies his discussion by focusing on utility damages, and the ecological damages in the Sterner-Persson model similarly appear in the utility function. We are not aware of previous work incorporating direct capital damages in cost-benefit IAMs.

3 Methodology

3.1 Modeling framework

We employ a matDICE, a MATLAB-based implementation of DICE that we have written and optimized for Monte Carlo analysis. (The source code is available in the supplementary material.) We run the model in ten-year time steps from 2005 to 2305. For our reference scenario, we employ the same MiniCAM-based three-century reference scenario used in the US government social cost of carbon analysis (Interagency Working Group on the Social Cost of Carbon, United States Government, 2010). We also employ a stabilization scenario calculated to yield a 50% chance of limiting warming to 2.5°C (Figure 6).

We replace the default DICE damage function with the damage functions listed in Table 1, calibrated such that all the functions are in agreement on climate damages at 2.5°C, assuming 0.3°C per decade of warming and the same level of wealth as in 2005. For our primary calculations, we set the calibration point to agree with the default DICE 2007 calibration (1.77% of GDP loss at 2.5°C). We employ a lower bound to output of $730/person/year. (See the discussion in Weitzman, 2009, on bounding damages with a parameter akin to the value of a statistical life.)

Following the US government analysis, we treat climate sensitivity as an uncertain parameter with a Roe and Baker (2007) distribution, truncated at 10°C per CO_2 doubling and calibrated such that the median value is 3°C per CO_2 doubling and the 67% range is approximately 2 to 4.5°C per CO_2 doubling. We take one thousand samples evenly from the distribution, and we use Latin hypercube sampling when considering more than one uncertain parameter.

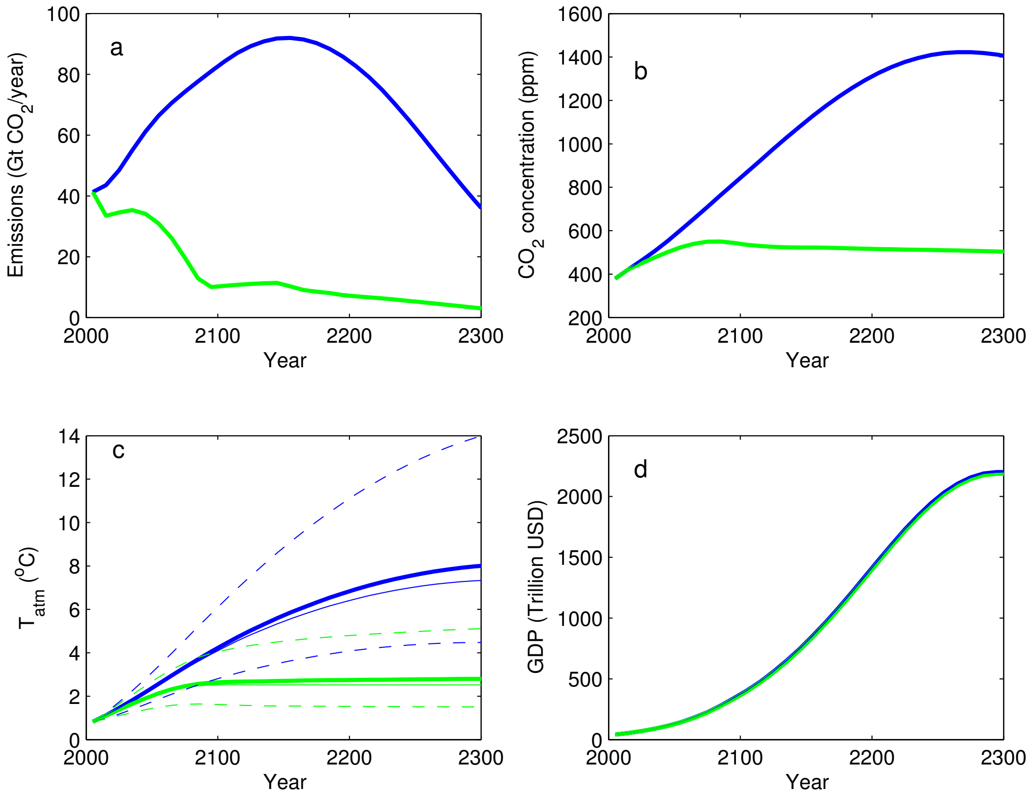

Figure 6: Reference (blue) and stabilization (green) scenarios used for the SCC calculations in this paper. Dashed lines indicate 5th and 95th percentile values for temperature, while the thin solid lines indicate median projections and the heavy solid lines indicate expected values. Projections shown here exclude the deleterious effects of climate damages on GDP and thus emissions. These effects are taken into account when calculating the SCC.

For the reference scenario, the standard DICE damage function, and a flat 3% discount rate, our model yields a 2010 SCC of $33/ton CO_2. This value which can be compared to the value of $29/ton calculated with DICE for the same year, scenario, and discount rate in the U.S. government analysis. The slight difference is largely attributable to a change in the calibration of the climate and carbon cycle transfer coefficients between DICE 2007, used in the U.S. government analysis, and DICE 2010, whose values we employ.

3.2 Discounting and risk aversion

The social cost of carbon is defined as the change in expected welfare from a unit emission of carbon dioxide in a given year, normalized to change in expected welfare from a unit of consumption in the same year. Note that it is distinct from "deterministic SCC" values, which are ratios of the corresponding changes in welfare, conditioned upon a specific state of the world. For zero risk aversion, the expected deterministic SCC is equal to the SCC, but this equality does not generally hold. In the presentation of our results, we show both the SCC and the distribution of deterministic SCC values.

In the isoelastic utility function employed by DICE and other IAMs, the marginal utility of consumption η serves as both the coefficient of relative risk aversion and the inverse of the intertemporal elasticity of substitution. The value of η and the pure rate of time preference ρ are related to the discount rate r and the growth rate of (effective) per capita consumption g via Ramsey's rule:

$$1+r=(1+\rho)(1+g)^{\eta} \tag{4}$$

Increasing risk aversion while holding the pure rate of time preference ρ constant will therefore also increase the discount rate.

The U.S. government SCC analysis used flat discount rates of 2.5%, 3% and 5% per year, with 3% being the central value. It chose not to disaggregate the values into η and ρ along lines of equation 4. Because the growth rates in that analysis's reference scenarios (as in our scenarios) decline to zero between 2100 and 2300, the choice of flat discount rates is strictly consistent only with η = 0. (This choice is consistent with the U.S. government analysis's risk neutrality, but inconsistent with its description of a plausible range for η as being between 0.5 and 4.)

In our analysis, we vary η and ρ such that the average discount rate r over 2015-2115 remains fixed at the U.S. government analysis's central value of 3% per year. We choose three different values of η (0, 1.0, and 1.4), which, in light of the average 2.03% annual growth rate between 2015 and 2115, lead to selection of values of ρ of 3.0%, 0.95% and 0.14% per year, respectively. These choices allow us to investigate the implications for the SCC of different values of the marginal utility of consumption while retaining consistency with the initial discount rates used in the U.S. government analysis. Within the constraints of the isoelastic utility function, however, it is not readily possible to isolate the two different effects of increasing η – increasing risk aversion and increasing the weight placed on damages in the slower growing 22nd and 23rd centuries.

3.3 Disaggregation of damages

Damage specifications Xa and Xb progressively disaggregate the standard DICE damage function. DICE treats catastrophic damages through their expected value; Xa separates the damage function into a deterministic gradual damages term and an uncertain threshold damages term (in a fashion similar to PAGE). To separate out catastrophic damages, we note that Nordhaus (2007) estimates risk-neutral expected damages from catastrophic climate change are responsible for 66% of total damages at the 2.5°C calibration point. We also note that Nordhaus and Boyer (2000) define a catastrophe as causing 30% loss of global GDP indefinitely. Taking these as given, we then calibrate a damage function of the form

$$D(T) = a_1 m(T) T^b + a_2 / \Big(1 + \exp(10(T_c - T))\Big) \tag{5}$$

where $m(T)$ is a multiplier, equal to 1 at low-to-moderate values of T, that accounts for cases where extrapolations of the probability of catastrophic damages causing 30% loss of GDP would exceed 100%, T_c is the uncertain temperature threshold for a catastrophe, and the factor of 10 controls the warming range over which the catastrophe occurs. Values are calibrated such that non-catastrophic damages at 2.5°C are equal to 0.61% of GDP and so that expected damages match their standard DICE value.

Damage specification Xb distributes the damages in Xa between output, capital, and Sterner-Persson-type environmental goods. Nordhaus (2007) attributes about one-quarter of non-catastrophic damages at 2.5°C to his “ecosystems and settlements” sector; we assume that about two-thirds of those damages are to environmental goods, and therefore infer that about 15% of total consumption is accounted for by environmental goods (i.e,. we set γ in equation 2 to 0.15). Assuming that another third of this sector constitutes damages to capital, and that one third of damages due to coastal impacts are also to capital, we infer that another 15% of damages occur via capital losses. For a given damage function, we calculate damages to capital as

$$D_{\text{cap}}(T) = 1 - (1 - \Omega(D(T)))^{f_{\text{cap}}/\alpha}; \tag{6}$$

where f_{cap} is the share of total damages caused through capital and α is the elasticity of capital in the production function (0.3).

Damage specification Xc builds upon Xb by introducing uncertainty. We let b be log normally distributed with a mean of 2.0 and a one-sigma uncertainty of 1.7x. We let expected damages at 2.5°C be log normally distributed with a mean of 1.77% of global GDP (matching DICE) and a one-sigma uncertainty of 2.3x. We keep gradual damages at one-third of expected damages. The damage resulting from a catastrophe is normally distributed, with a mean of 30% of global GDP and a standard deviation of 10%. The elasticity of environmental goods in the utility function is triangularly distributed between 0.5 and 1.0, with a mean of 0.75. Both the share of environmental goods in the utility function and the fraction of damages accruing through capital impacts are triangularly distributed between 0 and 0.15, with a mean of 0.075. The expected GDP path is very close to that calculated using the standard DICE damage function; the median is higher than with the DICE damage function, and 5th percentile of output is considerably lower. With this damage function, there is an ~1.6% probability in the reference scenario that our

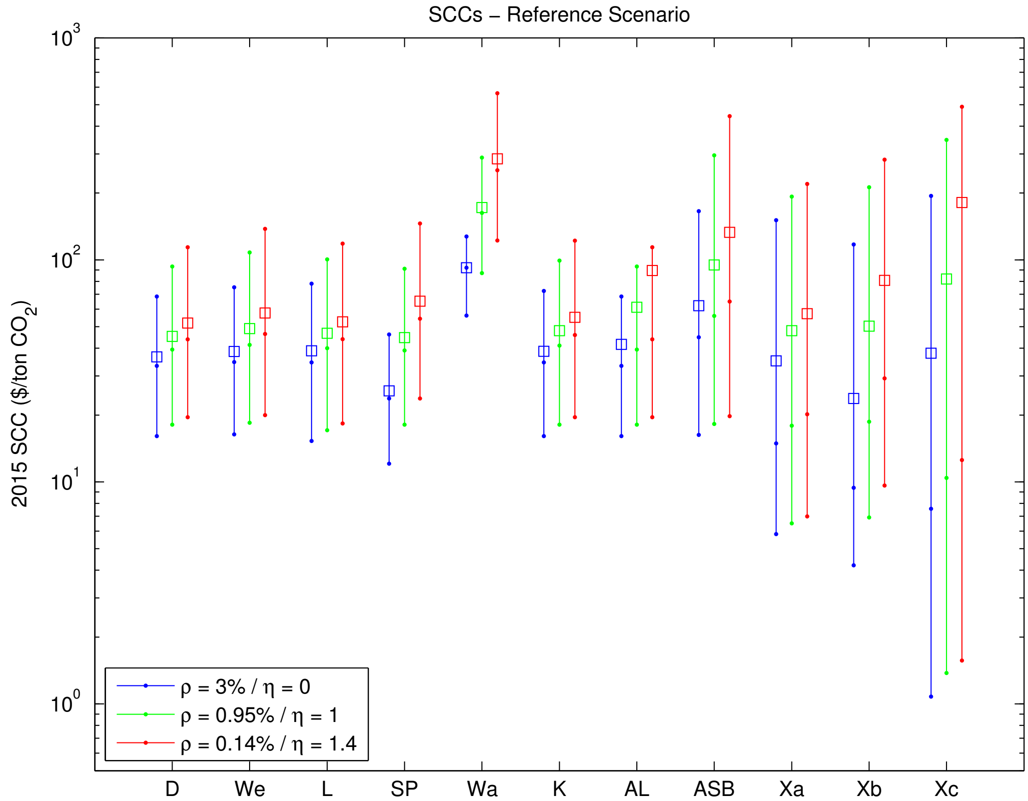

Figure 7: 2015 SCC values calculated using different damage functions and different disaggregations of a 3% per year average discount rate. Squares indicate the SCC, while dots connected by lines indicates 5th, 50th, and 95th percentiles of the deterministic SCC.

23rd century descendants are less wealthy than we are, and an ˜0.7% chance that they are eking out a marginal existence in extreme poverty, with a global GDP of $2/person/day.

4 Results and Discussion

The consequences of changing the damages specification depend strongly on the elasticity of the marginal utility of consumption (Table 3, Figure 7). For the risk neutral case ($\eta = 0$), specifications with similar expected damages yield similar results. Thus D, We, K, L and Xa cluster in the range of \$35-\$39/ton CO_2 emitted in 2015. Because of the modestly (AL) or highly (ASB) uncertain exponent in their damage functions, AL and ASB are associated with higher SCC values of \$42 and \$62/ton, respectively. Wa is the highest, at \$92/ton; this reflects the increasing the severity of damages under this specifications as the world grows wealthier

Table 3: SCC values and quantiles of the deterministic SCC for different levels of risk aversion and pure rate of time preference in the reference scenario

	$\rho = 3\%, \eta = 0$				$\rho = 0.95\%, \eta = 1.0$				$\rho = 0.14\%, \eta = 1.4$			
	SCC	**50th**	**5th**	**95th**	**SCC**	**50th**	**5th**	**95th**	**SCC**	**50th**	**5th**	**95th**
D	$37	$33	$16	$68	$45	$39	$18	$93	$52	$44	$20	$114
We	$39	$35	$16	$75	$49	$41	$18	$108	$58	$46	$20	$138
L	$39	$35	$15	$78	$47	$40	$17	$101	$53	$44	$18	$118
SP	$26	$24	$12	$46	$45	$39	$18	$91	$65	$54	$24	$146
SP*	$49	$46	$23	$86	$70	$62	$29	$137	$89	$76	$33	$194
Wa	$92	$92	$56	$127	$172	$163	$87	$289	$285	$253	$122	$563
K	$39	$35	$16	$72	$48	$41	$18	$99	$55	$46	$20	$122
AL	$42	$33	$16	$68	$61	$39	$18	$93	$90	$44	$20	$114
ASB	$62	$45	$16	$166	$95	$56	$18	$296	$133	$65	$20	$444
Xa	$35	$15	$6	$151	$48	$18	$7	$193	$57	$20	$7	$220
Xb	$24	$9	$4	$117	$50	$19	$7	$212	$81	$29	$10	$283
Xb*	$51	$27	$10	$188	$83	$38	$13	$269	$115	$49	$16	$325
Xc	$38	$8	$1	$194	$82	$10	$1	$347	$181	$13	$2	$489
Xc*	$45	$10	$1	$216	$85	$11	$1	$353	$181	$13	$2	$484

* Sterner-Persson utilities adjusted for fixed first-period relative prices.
All values in 2007 US dollars per metric ton CO_2 emitted in 2015.
η and ρ chosen to maintain an average discount rate of 3% per year over 2015–2115.

Table 4: SCC values and quantiles of the deterministic SCC for different levels of risk aversion and pure rate of time preference in the stabilization scenario

	$\rho = 3\%, \eta = 0$				$\rho = 0.95\%, \eta = 1.0$				$\rho = 0.14\%, \eta = 1.4$			
	SCC	**50th**	**5th**	**95th**	**SCC**	**50th**	**5th**	**95th**	**SCC**	**50th**	**5th**	**95th**
D	$34	$30	$14	$68	$40	$35	$16	$86	$45	$38	$17	$101
We	$35	$30	$14	$70	$41	$35	$16	$90	$47	$39	$17	$106
L	$35	$30	$13	$74	$41	$35	$15	$90	$45	$38	$16	$103
SP	$23	$21	$11	$44	$40	$34	$16	$84	$57	$47	$21	$130
SP*	$52	$46	$21	$104	$71	$60	$26	$157	$88	$72	$30	$206
Wa	$138	$136	$70	$211	$250	$229	$106	$465	$375	$323	$139	$799
K	$34	$30	$14	$69	$41	$35	$16	$92	$47	$38	$17	$110
AL	$41	$30	$14	$68	$53	$35	$16	$86	$64	$38	$17	$101
ASB	$47	$32	$12	$131	$60	$37	$14	$170	$69	$42	$15	$203
Xa	$30	$11	$5	$89	$41	$12	$6	$120	$48	$14	$6	$170
Xb	$21	$7	$4	$58	$43	$13	$6	$137	$68	$19	$8	$253
Xb*	$49	$21	$9	$148	$78	$28	$12	$272	$106	$34	$14	$382
Xc	$37	$6	$1	$257	$70	$8	$1	$418	$108	$9	$2	$558
Xc*	$47	$7	$1	$322	$77	$8	$2	$444	$110	$9	$2	$555

* Sterner-Persson utilities adjusted for fixed first-period relative prices.
All values in 2007 US dollars per metric ton CO_2 emitted in 2015.
η and ρ chosen to maintain an average discount rate of 3% per year over 2015–2115.

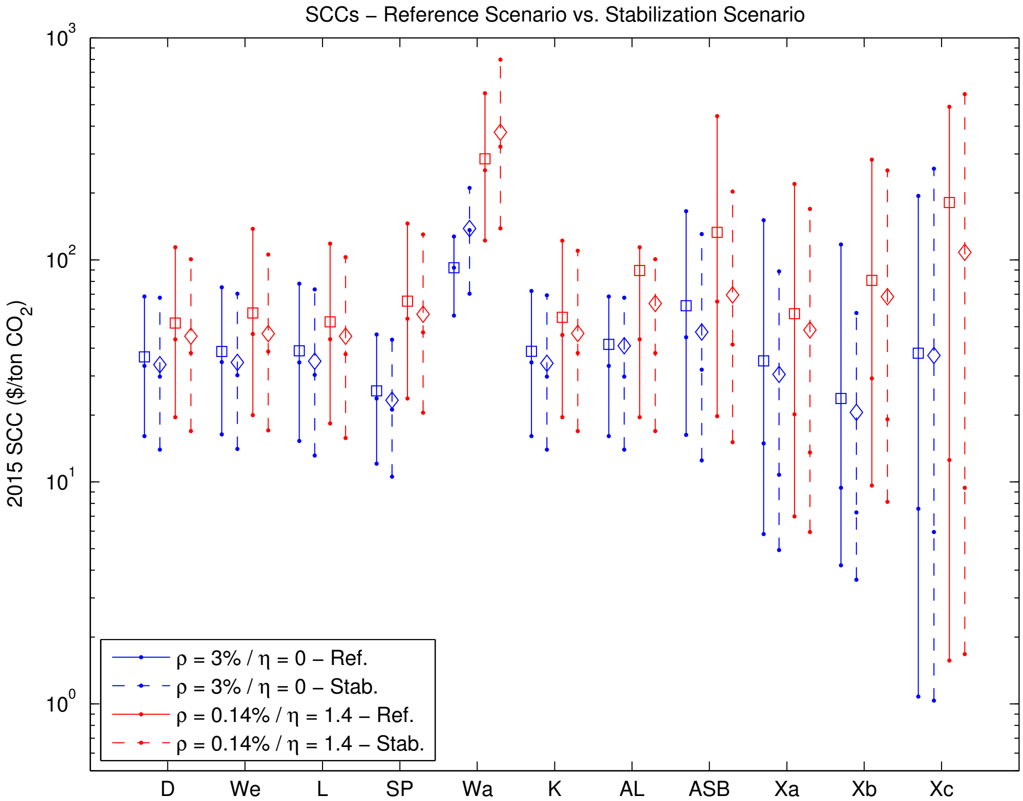

Figure 8: 2015 SCC values calculated using different damage functions and different disaggregations of a 3% per year discount rate. Solid lines indicate values for the reference scenario, while dashed lines indicate values for an emissions stabilization scenario with a 50% chance of limiting warming to 2.5°C.

(compare the two lines representing Wa in Figure 1) As noted previously, due to relative price effects, employing a Sterner-Persson damage function decreases the SCC ($24-$25/ton for SP and Xc). When these SCCs are corrected for price effects, they roughly double.

When risk aversion is taken into account, the SCC depends not only on expected damages but also on the variance of damages. Since we keep the average discount rate over 2015-2115 constant while increasing risk aversion, SCC values from deterministic damage functions with an approximately quadratic form increase only slightly. This increase is due in part to the lowering of the discount rate in the 22nd and 23rd century, when the reference consumption growth rate slows, and in part to the risk associated with an uncertain climate sensitivity.

Wa, though deterministic, responds more severely because of its high sensitivity at high levels of wealth. SCCs associated with uncertain damage specifications (e.g., AGB and AL) grow considerably more rapidly with risk. The degree of this

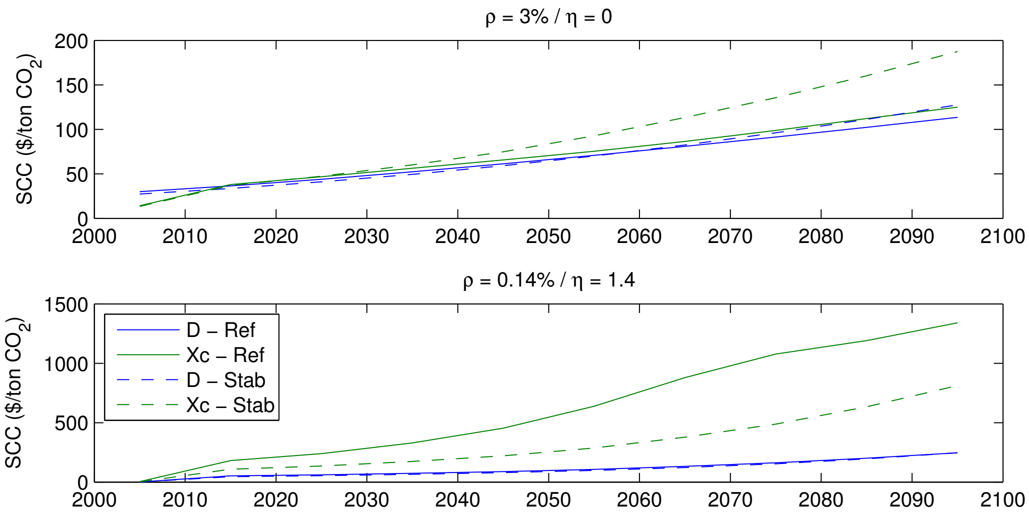

Figure 9: 21st century SCC values calculated using damage functions D (blue) and Xc (green) and different disaggregations of a 3% per year discount rate. Solid lines indicate values for the reference scenario, while dashed lines indicate values for an emissions stabilization scenario with a 50% chance of limiting warming to 2.5°C.

effect depends upon the variance of damages, with the most uncertain damages leading to the greatest growth in SCC. The most uncertain damage function (Xc) exhibits this effect most dramatically, with the SCC growing from a risk-neutral \$38/ton with $\eta = 0$ to \$150/ton at $\eta = 1.4$, as an increasing amount of weight is placed on the small number of states of the world in which the future is poorer than the present.

As η increases, the SCC penalty associated with adopting a Sterner-Persson utility function also disappears. At $\eta = 1$, for example, SCC values from D and SP are nearly identical. This is because the future in the Sterner-Persson world is poorer in effective consumption terms; at $\eta = 0$, the future therefore contributes less to welfare, while at $\eta = 1$, marginal utility is proportional to utility, and so this effect goes away. At $\eta > 1$, poorer states of the world contribute more than proportionally to expected social welfare.

In general, SCC values calculated off the stabilization scenario are moderately lower than SCC values calculated off the reference scenario (Table 4, Figure 8). Employing AGB magnifies this reduction, as for most climate sensitivities, the stabilization scenario avoids the high-temperature portion of the damage function, where the consequences of higher exponents are felt most strongly. Wa exhibits the converse effect: with this function, the SCC is higher under the stabilization scenario. Later in the 21st century, both D and Xc exhibit a similar phenomenon in the risk neutral case (Figure 9). These examples provide a concrete illustration of the concerns about non-convex damage functions raised by Kopp and Mignone

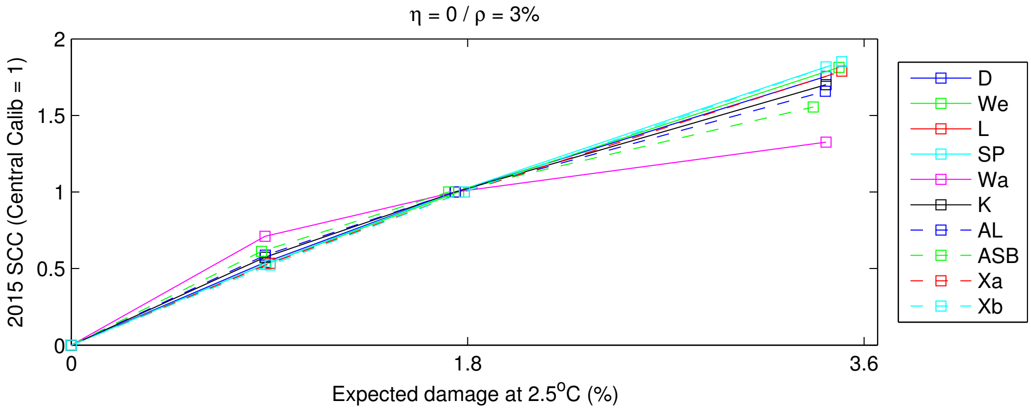

Figure 10: 2015 SCC values calculated using different damage functions and different disaggregations of a flat 3% per year discount rate, using a 2.5°C calibration level double or half the default DICE level. SCC values shown are normalized to the SCC for the central calibration point (1.8% damages at 2.5°C).

(2011). With these damage functions, emissions and growing wealth in the reference scenario are sufficient to carry temperature well over an inflection point beyond which the marginal damages associated with warming start decreasing.

For a given damage function, adjusting damages at the 2.5°C calibration point downward has a roughly linear effect on the SCC (Figure 10). For most damage functions, cutting calibration damages in half decreases values by about 40%-50%, while doubling them has a similar but slightly muted effect, increasing SCC values by about 60%-80%. This muting is due to the upper bound on most damage functions; higher calibration damages bring the damage function closer to the bound, and thus into non-convexity, at lower temperatures. The muting effect can be seen most clearly with Wa, which, as noted previously, is well in the non-convex range of behavior under the central calibration. The SCC calculated under Wa decreases by about 30% in response to a halving of 2.5°C calibration damages and increases by about 30% in response to a doubling of calibration damages.

5 Conclusions and Next Steps

Our analysis highlights the importance of jointly considering risk aversion and uncertainty in damages when estimating the SCC. For a certain damage function but uncertain climate sensitivity, increasing risk aversion modestly increases the SCC. For an uncertain damage function – even one that yields the same expected damages – increasing risk aversion can greatly increase the SCC. Our hybrid uncertain damage function – which yields nearly the same expected future GDP path as the standard DICE damage function, but acknowledges a small chance that climate change could make the future less well off than the world today – yield SCC values that go from being nearly equal to the SCC calculated with the standard DICE damage function with no risk aversion to nearly triple it with a coefficient of relative risk aversion of 1.4.

Because we employed a standard isoelastic utility function, we could not isolate the effects of increasing risk aversion from the effects of a declining intertemporal elasticity of substitution. Fundamentally, this is because the isoelastic utility function requires the elasticity of intertemporal substitution and the level of risk aversion to be controlled by a single elasticity of the marginal utility of consumption (η). Yet empirical psychological work (e.g., Atkinson et al., 2009) indicates that individuals are not equally averse to risk and to intertemporal inequality; future work should therefore examine the joint sensitivity of the SCC to damage specification and risk aversion in models with utility functions that do not require these parameters to be coupled (Traeger, 2009).

In addition to the form of the damage function, the calibration of the damage function also matters. The risk-neutral SCC scales approximately linearly with damages at the calibration point. If the uncertainty in this calibration is large – as seems likely, given that FUND estimates non-catastrophic damages of about 0.9% to 1.6% of GDP at 2.5°C warming while DICE estimates non-catastrophic damages of 0.6%, and that both the likelihood of climate catastrophes and their economic consequences are poorly characterized – then both form and calibration can have effects on the SCC of similar magnitude.

Both calibration of the damage function and identification of a suitable form can be advanced through both empirical and modeling work. Emerging retrospective analyses (e.g., Lobell et al., 2011) can help characterize damages for 0.8°C of warming realized to date more accurately, while modeling economic impacts at levels of warming significantly higher than 2.5°C (e.g., New et al., 2011) can advance the construction of damage functions beyond the stage of fitting a curve to two points.

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