Climate Impacts on Economic Growth as Drivers of Uncertainty in the Social Cost of Carbon

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ABSTRACT

We reexamine estimates of the social cost of carbon (SCC) used by agencies as the price of carbon emissions in cost-benefit analysis, focusing on those by the federal Interagency Working Group on SCC (IWG). We show that the models used by the IWG assume continued economic growth in the face of substantial temperature increases, which suggests that they may not capture the full range of possible consequences of climate change. Using the DICE integrated assessment model, we examine the possibility that climate change may directly affect productivity and find that even a modest impact of this type increases SCC estimates substantially. The SCC appears to be highly uncertain and sensitive to modeling assumptions. Understanding the impact of climate change therefore requires understanding how climate-related harms may affect productivity and economic growth. Furthermore, we suggest that misunderstandings about growth assumptions in the model may underlie the debate surrounding the proper discount rate.

1. INTRODUCTION

In the absence of a nationwide carbon tax or cap-and-trade system, the United States is addressing human-induced climate change through reg-

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ulations, such as fuel-efficiency standards for vehicles and emissions standards for new and existing power plants. Agencies designing and implementing these regulations are required to show that they are cost justified through cost-benefit analysis, and for this purpose they need a monetized value for marginal reductions in emissions of carbon dioxide (CO_2), the primary greenhouse gas implicated in global warming. This value is known as the social cost of carbon (SCC).[1]

In 2010, the Interagency Working Group on the SCC (IWG), consisting of 12 federal agencies, developed a unified estimate of the SCC for use by all agencies in the federal government (IWG 2010).[2] The IWG estimated the value of the SCC by using three commonly used integrated assessment models (IAMs) with integrated representations of the climate and the economy. The IWG ran each model under a business-as-usual assumption, ran them again with an additional ton of CO_2, and computed the SCC as the present-value difference in consumption between these two cases. For each model, the IWG computed the SCC for a variety of scenarios, sensitivities of the climate to increased atmospheric CO_2, and discount rates to produce a range of estimates. It then averaged the results across scenarios and models. The IWG's central value of the

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1. The SCC is used in analysis of any regulation affecting carbon dioxide (CO_2) emissions, even those whose goal is not emissions reduction. The IWG estimate discussed here was introduced in conjunction with Department of Energy small electric motor efficiency standards (Energy Conservation Standards for Small Electric Motors, 75 Fed. Reg. 10,874 [March 9, 2010]). More recently, the Environmental Protection Agency used the SCC to calculate the benefits from its proposed emission regulations under section 111(d) governing existing power plants (U.S. EPA 2014). Rose (2012) and Nordhaus (2014) review uses of the SCC in regulatory analysis. Nordhaus reports that as of January 2014, SCC estimates had been used in calculating benefits of 58 proposed or final regulations.

2. Greenstone, Kopits, and Wolverton (2013) discuss the IWG process from the perspective of participants in it. Other discussions of the IWG include Kopp et al. (2012), Kopp and Mignone (2012), Masur and Posner (2011), Johnson and Hope (2012), and Nordhaus (2014).

2010 SCC was \$21/tCO_2.[3] The IWG updated its study in 2013, with a new central value for the 2010 SCC of \$33/tCO_2 (IWG 2013). Estimates by private researchers are roughly in line with these values.

In this study, we reexamine the IWG's estimates of the SCC. For illustrative purposes, we focus on the estimates made using the DICE model, the most widely used IAM with a long history of use in studies of the costs of global warming (Nordhaus 1993, 2008). Our conclusions, however, apply more generally. We make four points.

First, DICE and the other models used by the IWG implicitly assume that the economy will continue to grow even in the face of substantial global warming, so that people living at the end of the modeled time period are vastly richer than we are today notwithstanding the harms from large temperature increases. Second, the assumption of continued growth is built into the structure of DICE. Harms from climate change are assumed to affect the economy in such a way that they cannot significantly reduce long-term growth almost regardless of how high they are. While the possibility of continued growth cannot be ruled out, other possibilities should not be precluded by the structure of the model. Third, when we relax the assumption of continued growth in the face of climate change, SCC estimates increase, in some cases by orders of magnitude. There is far more uncertainty in SCC estimates than has been recognized.[4] Fourth, the long-standing controversy over the choice of the discount rate may be driven in part by the lack of recognition that most estimates of optimal climate policies assume continued growth in the face of climate change.

2. BACKGROUND AND MOTIVATION: ECONOMIC GROWTH IN THE FACE OF SUBSTANTIAL CLIMATE CHANGE

When estimating the effects of activities that contribute to climate change, analysts must make assumptions concerning expected future emissions of CO_2 and other greenhouse gases, determine how cumulative emissions over time affect the climate, and translate those physical changes into harms to the economy. A standard tool for this purpose is

3. Notwithstanding the common use of terms that refer to carbon (for example, the SCC or a carbon tax), all SCC values used in this paper are given in metric tons of CO_2, not C, as is also standard in the literature. A molecule of CO_2 weighs 44/12 of a molecule of C. For consistency with the IWG, we state SCC values in 2007 dollars.

4. While it is clear, once pointed out, that assumptions about how climate change affects economic growth are of primary importance, the point is routinely missed (see, for example, Greenstone, Kopits, and Wolverton 2013; Anthoff and Tol 2013).

the IAM, which combines insights from science and economics in a consistent manner. IAMs include representations of the economy and of the climate, with the two systems interacting: the economy produces emissions, and emissions (via climate change) in turn affect the economy. To be tractable, IAMs use simplified representations of both the science and the economics.

The IWG used versions of three widely used IAMs to estimate the SCC—DICE (Nordhaus 2008), PAGE (Hope 2006), and FUND (Anthoff, Tol, and Yohe 2009)—and ran them under a number of different economic scenarios, averaging the results from all three to produce its SCC values. The IWG also conducted sensitivity analyses over the extent to which surface temperatures rise with increased atmospheric CO_2 (climate sensitivity). It found a 95th percentile SCC value of \$65, roughly three times its central value of \$21. For simplicity, in our analysis we focus on a single model (DICE), economic scenario (IMAGE),[5] and climate sensitivity (3°C/doubling of CO_2, the median in the distribution used by the IWG). The 2010 SCC is \$32/tCO_2 for these choices.[6]

DICE is a Ramsey-Cass-Koopmans growth model with an added climate externality. Economic activity, which is represented by a Cobb-Douglas production function, produces emissions of CO_2 that are based on an assumed emissions intensity, which declines over time based on an exogenously determined pathway. These CO_2 emissions are fed into a simple representation of the ocean and atmosphere to determine increases in CO_2 concentration, which then lead to higher surface temperatures. Temperature increases result in harms that, through an assumed damage function, reduce economic output. The model is stepped forward in 10-year increments for several hundred years, keeping track of stock variables such as capital, population, and CO_2 in the atmosphere and ocean through specified laws of motion. To calculate the SCC, the model is run twice, once under business-as-usual assumptions and a

5. The IMAGE scenario was developed with the Integrated Model to Assess the Greenhouse Effect as part of the Stanford Energy Modeling Forum's EMF 22 exercise (Clarke et al. 2009).

6. The update (IWG 2013) involved recalculating SCC values with updated model versions, including revisions to DICE. In the update, the central value for the 2010 SCC was \$33/tCO_2, and the 95th percentile estimate was \$90/tCO_2. The IWG reported updated values for individual models only for 2020 rather than 2010 SCC, which complicates comparisons, but most results suggest modest increases. (See online Appendix B.) The updated 2020 SCC value for DICE, IMAGE, and 3 percent discount rate is \$48/tCO_2. In light of our finding of high uncertainty in SCC values, we report values to only two significant figures rather than to three significant figures as in IWG (2010).

second time with one additional ton of CO_2 emitted in a specified year. The SCC for that year is the present-value difference in consumption in the two cases. Because DICE is a global model, with the entire world considered as a single unit, the SCC computed with DICE can be thought of as the global marginal harm from CO_2 emissions.

The IWG modified all three of the models it used so that its results were comparable and could be averaged. The models were tuned to reproduce a common set of economic trajectories. In DICE, this tuning meant imposing an exogenous path of productivity increases to produce the assumed economic trajectory. The IWG also fixed the savings rate at 22 percent, roughly the optimum in DICE, and imposed an exogenous CO_2 emissions trajectory (which meant that emissions were not a function of economic output). Finally, it used a fixed discount rate as required by the Office of Management and Budget's Circular A-4 instead of allowing the discount rate to be determined endogenously in the model. To ensure that none of these changes to DICE drive its results, we use DICE both as modified by the IWG (IWG-DICE) and without these modifications (standard DICE). We use the 2007 version of DICE because the IWG appears to have begun with that version before making its modifications, and for simplicity, we retain the assumption of fixed savings.[7]

The motivation for our study is the observation that the IWG models implicitly assume that society will grow far wealthier in the future even if temperatures increase by amounts that many scientists believe may cause substantial hardships (IPCC 2013, 2014a, 2014b).[8] The IMAGE scenario posits that, in the absence of climate change, people alive in the year 2300 will be 35 times wealthier on a per capita basis than we are today. With climate change, IWG-DICE projects under this scenario that the global mean temperature will rise more than 6°C by 2300, an

7. An Excel version of the 2013 version of DICE can be found at the Web site of William Nordhaus (the developer of DICE); see William D. Nordhaus, DICE-2013R Model as of November 15, 2013 http://aida.wss.yale.edu/ñordhaus/homepage/Web-DICE-2013-April.htm). We have recoded the 2007 and 2010 versions of DICE into Python with a Web-based front end to run the model (Center for Robust Decision Making on Climate and Energy Policy, webDICE [http://webdice.rdcep.org]; the code is available at https://github.com/RDCEP/chicagowebdice). For consistency with the IWG DICE results, we disable here the fossil fuel limit in standard DICE that forces CO_2 emissions to drop to 0 after 6 trillion metric tons of carbon are burnt (that is, 22 trillion metric tons of CO_2 are emitted). See online Appendix A for further discussion of IWG models and the IMAGE scenario.

8. Weitzman (2011) also notes the persistence of growth in the face of substantial climate change in DICE.

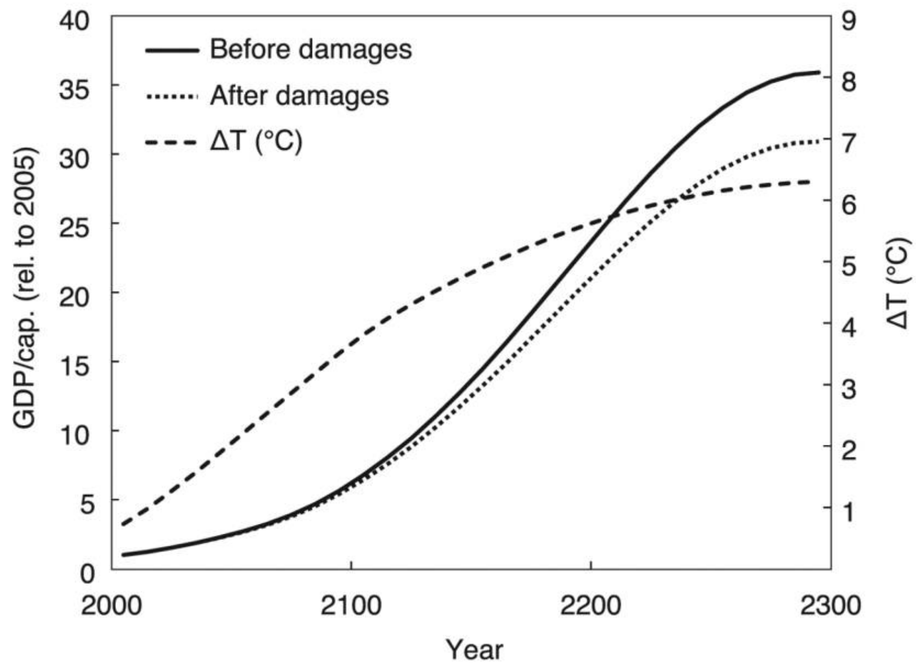

Figure 1. Evolution of per capita GDP from IWG-DICE (IMAGE scenario with climate sensitivity of 3°C/doubling). Future generations are much wealthier both with (*dotted line*) and without (*solid line*) climate change, despite temperature increase of over 6°C.

amount likely to lead to large-scale environmental change. Per capita income will nevertheless still be 30 times higher than today (Figure 1). The growth rate of the global economy is essentially unchanged by climate change, lowered by only .05 percent/year from an average annual rate of 1.34 percent (1.24 percent per capita) to 1.29 percent (1.19 percent per capita). Economic growth persists even though harms from climate change in this scenario eventually exceed 10 percent of the gross domestic product (GDP), a level that is often thought of as an economic disaster (Barro and Ursua 2011) (Figure 2). Because the growth rate is the dominant driver of consumption levels over long timescales and climate harms in IWG-DICE appear to have negligible impact on economic growth, climate change does not significantly affect consumption levels in the model.

While the possibility of continued growth in the face of substantial temperature increases cannot be ruled out, it should not be the only case considered. For an analysis of SCC values to be robust, it must explore

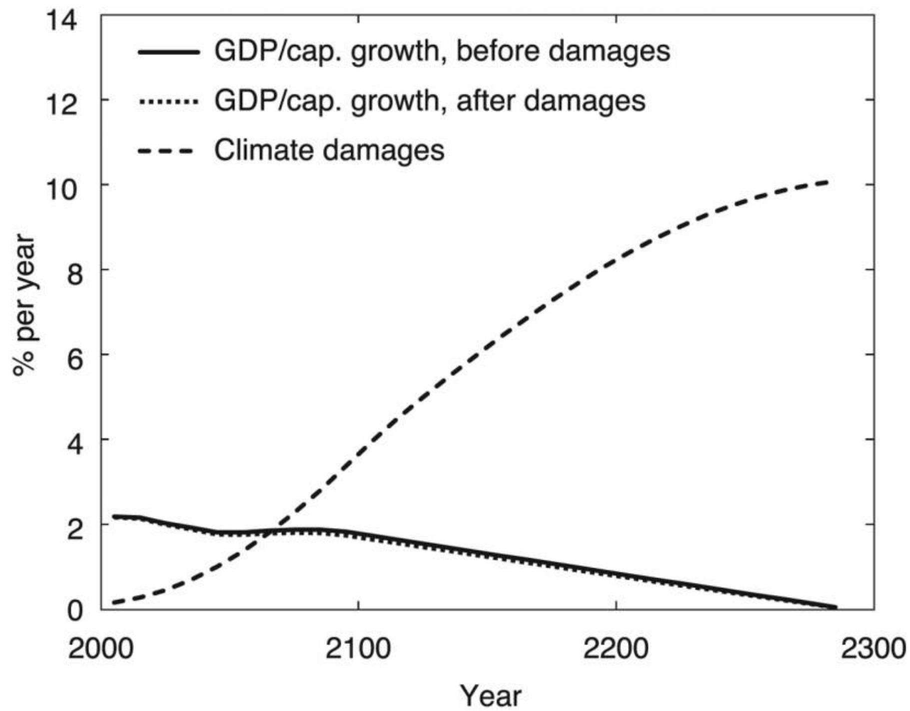

Figure 2. Evolution of GDP growth rate (percent/year) from IWG-DICE (IMAGE scenario with climate sensitivity of 3°C/doubling), and climate harms to output (also percent/year).

the possibility that climate change will have more substantial impacts. We believe however that the implicit assumption of continued growth is general to many estimates of the SCC. Although we show results from only one IWG model and scenario, standard DICE and FUND produce similar results. Both standard DICE and FUND project large temperature rises by the year 2300 under business-as-usual scenarios (increases of 7° and 8.5°, respectively) but negligible effects on future consumption. In standard DICE, per capita consumption is reduced from 37 times today's level to 33 times. In FUND, per capita consumption is reduced from 22 to 19 times today's level.[9]

9. See online Appendix C for analogs to Figures 1 and 2 for standard DICE and FUND. The FUND results are generated from the unmodified FUND model (http://www.fund-model.org). For the IWG estimates, FUND was modified analogously to the DICE modifications discussed here (IWG 2010). The code for the third model used by the IWG, PAGE, is not publicly available. The SCC values produced by PAGE are, however, roughly similar to those from FUND and DICE, which suggests that it has a similar assumption about growth.

More broadly, SCC estimates in the literature resemble those of the IWG. To date there have been over 200 estimates of the SCC from roughly 50 different studies (in addition to the IWG estimates). Tol (2008) reviewed these studies and, depending on the aggregation method used, found a mean SCC value ranging from \$34/tCO_2 to \$42/tCO_2 and a median of \$5/tCO_2 to \$25/tCO_2 (all in 1995 dollars). Figure 3 shows a histogram of the 2010 IWG SCC estimates across all models, economic scenarios, and climate sensitivities, overlaid with estimates of the SCC that use a 3 percent discount rate from Tol (2008). While we do not have access to the code used in most prior studies, the similarity of published SCC values to those of IWG-DICE suggests that many models may share similar implicit assumptions about the interaction of climate and economic growth.

3. STRUCTURAL ASSUMPTIONS

The assumption of continued growth in the face of substantial global warming is built into the structure of DICE. The model is designed in such a way that economic growth is nearly insensitive to climate damages.

The key equation for our purposes is the equation that determines how damages affect output Y_t:

$$Y_t = (1 - D_t)[A_t N_t^{1-\alpha} K_t^{\alpha}]. \tag{1}$$

The expression in square brackets is the output without harms from climate change. Labor supply in a given period N_t is determined exogenously and earns a fixed share of output equal to $1 - \alpha$. Capital K_t evolves according to the standard law of motion for capital, $K_{t+1} = K_t(1 - \delta) + sY_t$, with an assumed depreciation rate δ of 10 percent. In standard DICE, savings s can be either endogenous or, because results are relatively insensitive to savings rates, may be fixed at 22 percent, approximately the optimum for most parameter choices. (Most available versions of DICE, including IWG-DICE and the version of standard DICE shown here, use a fixed savings rate of 22 percent.) Total factor productivity (TFP), represented by A_t in the model, is specified exogenously.

Climate change in this formulation reduces usable output by the fraction D_t, a measure of harms expressed as a fraction of output. It is as if the damaged portion of output (D_tY_t) were simply thrown away. The relative magnitude of climate harms D_t is represented by a quadratic

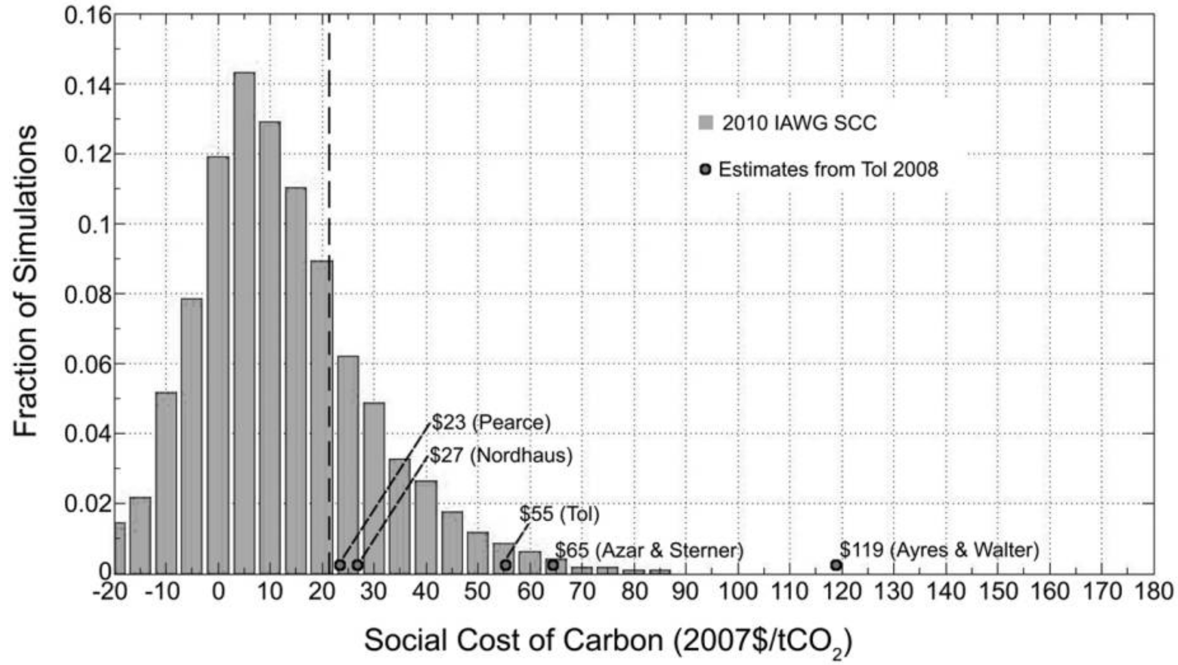

Figure 3. Distribution of 2010 IWG estimates of the year-2010 SCC from all three models for a 3 percent discount rate. Data were digitized from Figure A8 of IWG (2010). (Raw IWG SCC data are no longer available.) Dashed line is mean value across models, \$21/tCO_2. Mean (median) SCC values for DICE, PAGE, and FUND are \$28 (\$25), \$30 (\$12), and \$6 (\$0.5)/tCO_2 respectively. Dots show all SCC estimates from the Tol (2008) review with a 3 percent discount rate, as average values for each study. See online Appendix B for updated values from IAWG (2013).

function of the change in global temperature relative to the global mean in 1900:

$$D_t = 1 - \frac{1}{1 + a\Delta T_t^2}. \tag{2}$$

The damage function is calibrated (by setting a equal to .0028388) so that at a temperature change $\Delta T = 2.5°$, the economic loss D_t is 1.8 percent of GDP. This calibration reflects an analysis of studies of the harms from climate change (Nordhaus 2008; Nordhaus and Boyer 2000).

In this formulation, if climate damages were constant, they could not affect long-run economic growth at all, regardless of their severity. Output would simply be reduced at all times by a fraction D from the no-climate-change case. Climate change can affect the fractional growth rate $dY/Y/dt$ through only two pathways. Both are small effects related to the fact that damages grow over time as warming progresses.

The first pathway is related directly to the increase in damages over time. Economic growth is reduced by the rate of increase in damages as the temperature rises. In the baseline case that we examine, harms begin at 0 and eventually exceed 10 percent of GDP. That is, the economic output is reduced by 10 percent over 300 years, or ~.03 percent/year. The effect on growth is small because although harms become large, the timescale over which they rise is long.

The second pathway involves the effect of climate damages on savings. Because climate change reduces usable output, it also lowers the amount of output saved. (Savings rates are fixed in both versions of DICE used here.) Lowered savings reduces future levels of capital, which in turn leads to lower future output. This interaction slightly exacerbates the consequences of climate harms on output but again would leave long-run growth rate unchanged if damages were constant. With rising damages, the savings effect grows over time, which retards economic growth. As other authors have pointed out, this effect is small (see, for example, Fankhauser and Tol 2005; Stern 2013). Under the parameter choices used in IWG-DICE, the interaction of climate harms and savings accounts for the remaining .02 percent/year depression of the growth rate in the scenario we consider (see online Appendix D). Because both effects are small, they leave long-term growth rates of 1.3 percent essentially unchanged (Figure 2).

We test the robustness of the economic growth in the model to climate harms by increasing the magnitude of those harms to implausible values while retaining the structural assumptions in the model. We arbitrarily

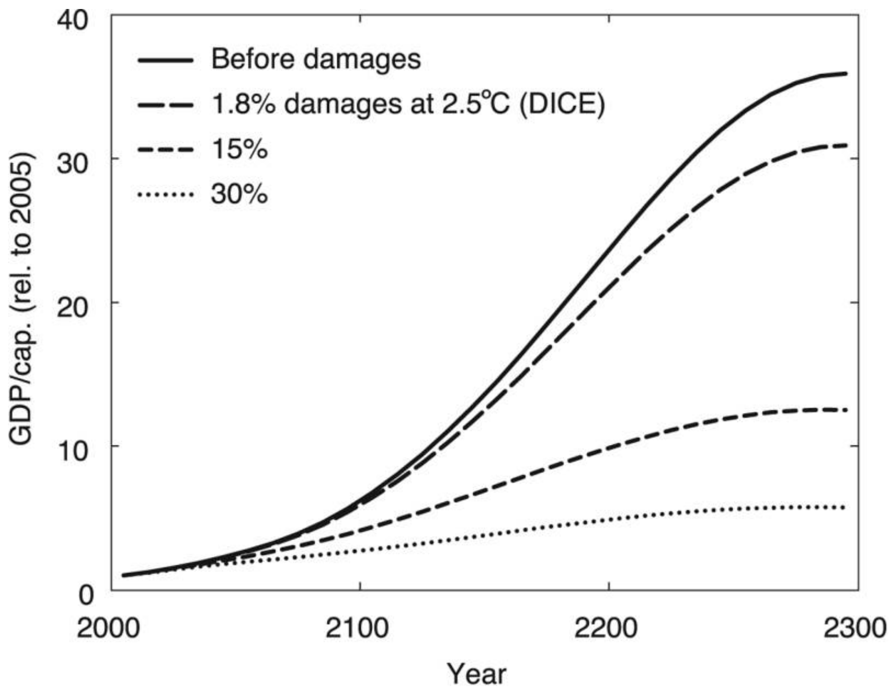

Figure 4. Per capita consumption levels as a multiple of per capita consumption in 2005, for IWG-DICE but with varying damage calibration points: as in the IWG model (1.8 percent of GDP for a 2.5° temperature increase), and at 15 percent and 30 percent of GDP for the same temperature increase.

increase the calibration value of the damage function by over an order of magnitude to 15 percent and to 30 percent of GDP. The most extreme value used is over six times the maximum of the plausible range of damages estimated by the Intergovernmental Panel on Climate Change (IPCC 2008) and yields climate-related losses of over 70 percent of GDP by 2300. (By way of comparison, year-over-year contraction in the United States during the Great Depression was 8.6 percent, 6.5 percent, and 13.1 percent in the years 1929–30, 1930–31, and 1931–32, respectively.) As can be seen in Figure 4, even these losses do not cause the economy to contract. Instead, society continues to become wealthier. The assumed exogenous factors driving growth in DICE outweigh any plausible effects of climate change.

4. MODIFICATION AND RESULTS

The robustness of growth in DICE suggests that the specification of harms from climate change may not reflect the full range of ways by which climate change may interact with the economy. The model has only four variables that can be affected by climate change: output *Y*, capital *K*, labor *N*, and productivity *A*. As specified, climate change reduces only output. Several authors have tested alternative representations of harms, including applying them to capital (for example, Ackerman, Stanton, and Bueno 2009; Kopp et al. 2012), but all yield economies that grow in the face of large temperature increases. We consider instead the possibility that climate change may directly reduce productivity.[10]

There are a number of ways that climate change might affect the productivity of the economy. Some effects, such as the destruction of ecosystems, would be permanent and could lead to long-term declines in growth because of the loss of the future benefits they might have provided. The productivity of outdoor sectors, such as agriculture and construction, might decrease, and future productivity gains may be harder to realize. For example, agricultural yields may decline if temperatures exceed critical thresholds, and outdoor workers may be affected by heat stress. Stern (2013) argues that existing infrastructure may become less productive because it is designed for the current climate, not for a changed climate. Climate change may force resources to be diverted to adaptations (building sea walls, building more robust infrastructure, or even moving cities inland), reducing investment in research or other productivity-enhancing activities (similar to the effects analyzed in Stokey [1998]). And increased expenditures on emissions reductions to prevent those harms (for example, renewable or nuclear electricity generation rather than gas- or coal-fired power plants) would divert resources from other efforts that could increase productivity. While disentangling level and growth effects is not straightforward, all of these harms may have long-run growth effects.

We take no view here on how, or whether, climate change will affect productivity. Indeed, it could be argued that the stress from climate change may force increases rather than decreases in productivity. Instead,

10. To our knowledge, only two prior papers consider this possibility, Fankhauser and Tol (2005) and Pindyck (2012). Fankhauser and Tol consider the possibility that climate change may have an indirect effect on productivity and hence growth. In their model, productivity growth is endogenous and is a function of labor and capital devoted to research and development (R&D). Climate change reduces usable output, as in DICE, and this reduces savings and capital available to the R&D sector, which slows growth. Pindyck's formulation lacks these microfoundations and directly applies climate harms to the growth rates of total factor productivity (TFP) (see Pindyck 2012, eq. 2 and related discussion).

we use a simple, arbitrarily chosen functional form to demonstrate the consequences should climate change reduce productivity. Our goal is to explore the sensitivity of the SCC to the implicit assumption that climate change does not affect productivity, not to estimate what the productivity effects actually will be.[11]

To allow for the possibility that climate change might reduce productivity, we modify the damage function in DICE so that it can affect TFP. In DICE, TFP, represented by A_t, is assumed to evolve according to an exogenously specified path with a growth rate g_{At} according to

$$A_{t+1} = (1 + g_{At})A_t. \tag{3}$$

(In IWG-DICE, the trajectory of A_t is specified so that output meets a specified trajectory, but we can derive implicit values for g_{At}.) We modify the DICE damage function by allowing an arbitrary fraction f of harms from climate change to reduce TFP instead of reducing output directly. To do this, we specify a new path of TFP, A_t^*, that is altered by climate change:

$$A_{t+1}^* = (1 - fD_t)(1 + g_{At})A_t^*, \tag{4}$$

where $A_0^* = A_0$. The remaining portion of harms, computed as $D_{t_{\text{Output}}} = 1 - (1 - D_t)/(1 - fD_t)$, directly reduces output as in equation (1). This formulation retains the same magnitude of harms from a temperature increase, expressed as a percentage of GDP, as in the original formulation. For example, the unmodified model specified the harms from a temperature change of 2.5° to be 1.8 percent of GDP. Our formulation produces the same fractional harms from that temperature increase. The only difference is that a portion of harms now applies to productivity and therefore directly alters long-term growth.

The effects of this modification are substantial, as can be seen in Figure 5. Applying $f = 5$ percent of harms to productivity means that income continues to grow until near the end of the 300-year period, but consumption in the year 2300 is only 30 percent of the no-climate-change case, that is, from 35 times present-day levels to 10 times present-day levels. With $f = 25$ percent, the economy collapses to $1,000/capita/year, near subsistence level, by the year 2300. Economic trajectories are acutely sensitive to the choice of f, allowing us to produce the full range

11. A substantial number of papers analyze climate policy in the context of endogenous technical change models. These papers focus on inducing technical change in the energy sector and how this possibility affects optimal abatement policies. They do not consider the possibility that climate change might reduce productivity. See Gillingham, Newell, and Pizer (2008) for a survey.

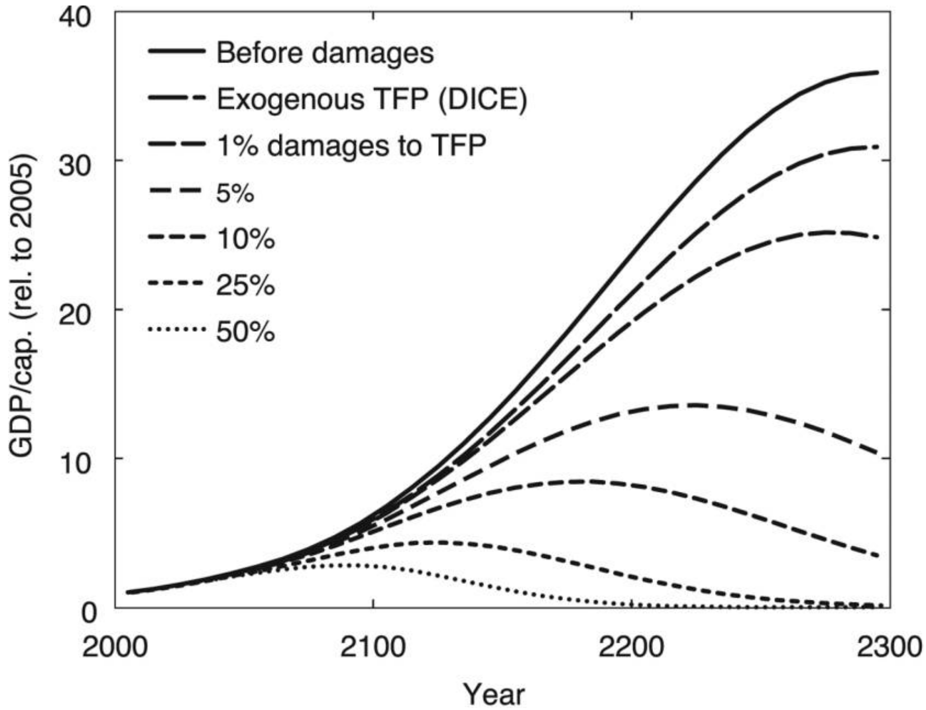

Figure 5. Per capita consumption levels as a multiple of per capita consumption in 2005, for IWG-DICE but with damages applied to TFP at specified levels. See online Appendix E for color version of figure.

of possible consequences of climate change, from only modest impacts to economic collapse.

We present the resulting SCC values from this experiment in Table 1. We show four different model specifications: (1) IWG-DICE modified so that a fraction of harms affect TFP, as in Figure 5 (with standard DICE shown for comparison),[12] (2) standard DICE with discount rate parameters roughly reflecting market rates, (3) standard DICE with lower parameter values (see Section 4 for a discussion of discounting),[13] and (4) standard DICE with an alternate, more physically realistic rep-

12. The code is available online (https://github.com/RDCEP/IWG-DICE).

13. The two key differences between IWG-DICE and standard DICE push in opposite directions. IWG-DICE assumes a fixed level of emissions, while standard DICE specifies emissions intensity so that emissions automatically decline if economic activity declines. IWG-DICE uses a fixed discount rate, as specified in Circular A-4, while standard DICE determines the discount rate endogenously. If the economy declines, the discount rate will be lower. Both effects can be large when f is large.

Table 1. Social Cost of Carbon, 2010 Values

	DICE Model, with 3% Discounting		Standard DICE Model with Endogenous Discounting		
Harms to TFP	IWG	Standard	Descriptive: $\eta = 2, \rho = 1\%$	Prescriptive: $\eta = 1, \rho = 0\%$	Modified Carbon Cycle: $\eta = 2\%, \rho = 1\%$
Unmodified	34	25	16	120	29
1%	51	34	21	270	34
5%	110	66	41	770	75
10%	160	96	71	1,300	150
25%	250	160	200	2,500	1,100
50%	320	230	610	3,800	3,800[a]

Note. SCC estimates for model cases described in the text. All values in \$2007/tCO_2, to two significant figures. For standard DICE, 2010 values are the average of 2005 and 2015 values. η is the elasticity of the marginal utility of consumption and ρ is the pure rate of time preference; the discount rate is $\eta g + \rho$, where g is the growth rate. See Section 4 and online Appendix E for additional discussion and examples. TFP = total factor productivity.

[a]With this set of parameter choices, the DICE model produces GDP per capita that falls below subsistence level (\$250/year/capita) during the 300-year analysis period. The model does not contain the flexibility to consider the consequences of this scenario. To avoid physically impossible results, we stop the SCC calculation in the year where a subsistence economy is reached on the theory that there can be no further harms.

resentation of ocean uptake of CO_2 (described in Glotter et al. 2014; see online Appendix E for further discussion).

As can be seen, SCC values are highly sensitive to the effects of climate change on productivity. In both the IWG and standard versions of DICE, if even 1 percent of climate harms reduce productivity, the SCC value increases by half again over values without this modification. At a 25 percent level, the SCC increases by factors of seven and six in the two versions of DICE. Even these increases may be underestimates of true SCC values for these levels of harms to productivity.

In cases in which climate change reduces growth, simplifications in DICE and in the IWG procedure begin to significantly affect the resulting SCC values for two reasons. First, as we increase the fraction of harms to TFP, the IWG choice of fixed discounting increasingly affects results, because the discount rate remains high even in economies that are shrinking (so that the true discount rate would be low). Fixed discounting can therefore artificially depress SCC values. Following the previous example, setting f equal to 25 percent in standard DICE produces a far larger increase in the SCC value with endogenous than with fixed discounting, which boosts SCC by an additional factor of two or three for high- and low-discount parameter choices, respectively.

Second, in those cases in which endogenous discounting permits the distant future to matter, accurate modeling of the long-term climate becomes important. The DICE representation of the atmosphere and ocean is realistic for only several decades and removes atmospheric CO_2 too quickly thereafter, so that DICE underestimates climate change and the resulting harms in the more distant future. Table 1 shows the effect of introducing into DICE a more physically realistic carbon cycle with lower long-term ocean CO_2 uptake (Glotter et al. 2014). Using this improved carbon cycle roughly doubles SCC even in low-f cases, in which economic growth is minimally affected and resulting high discount rates mean that the distant future is not highly valued. In high-f cases in which climate change reduces growth and therefore lowers discount rates, the improved carbon cycle means that SCC values increase by more than a factor of five.

The sensitivity of SCC values to treatment of climate harms is not the result of modifications made by the IWG, since results are similar in both IWG-DICE and standard DICE. We also test to verify that the sensitivity is not the consequence of the choice of a fixed savings rate of 22 percent and find that altered savings rates do not qualitatively affect results (see online Appendix E). Once we allow the possibility that climate change may reduce economic growth, SCC estimates face great uncertainty.

Because some of the cases explored here produce very high SCC values, it is important to carefully consider how to interpret these numbers. If taken at face value and used in cost-benefit analysis, high SCC values would seem to suggest stringent regulations. For example, if the SCC were \$3,800 ($f = 50$ percent, modified carbon cycle, either choice of discount rate parameters), an equivalent carbon tax (using purely physical conversion ratios and not adjusting for behavioral effects) would increase the price of a gallon of gasoline in the United States by 10-fold (to around \$38/gal) and the wholesale electricity price by nearly 100-fold (to around \$2.70/kWh). Regulatory policy such as power plant or vehicle emissions standards based on SCC values at this level would not likely be desirable. Our preferred interpretation is that very high SCC values suggest that the current level of emissions is far from optimal.

To understand this claim, recall that the SCC is not equal to the optimal carbon tax rate. The SCC measures the marginal benefit from a small reduction in emissions from the business-as-usual scenario. If the business-as-usual scenario is far from the optimum, the resulting SCC would bear no relationship to the marginal cost of the reduction: there might exist very inexpensive emissions-reduction options that would yield large benefits. The optimal tax is the price at which the marginal costs and benefits are equal. If the marginal benefit curve slopes downward and the baseline emissions are far from the optimum, the two numbers, the SCC and the optimal tax rate, can be quite different (see, for example, Mas-Colell, Whinston, and Green [1995, pp. 354–58] for a derivation).

Standard DICE illustrates exactly this point, because the model assumes emissions-reduction opportunities that are far less expensive than the marginal harms from additional emissions in many of the cases in Table 1. For example, with $f = 50$ percent, the 2010 SCC is \$3,800/tCO_2 for both discounting cases, but the model assumptions yield an optimal carbon tax for 2010 that is only a tenth as high, at \$330/tCO_2.[14] The optimal carbon tax and the SCC can differ widely if the harms from

14. The optimal carbon tax is calculated using the default assumptions in the 2007 version of DICE, including assumptions about the trajectory of costs of clean energy. In this case, because of the substantial harms from climate change, the carbon tax is driven high enough to induce an immediate shift to carbon-free energy. (In DICE CO_2 emissions fall immediately to zero.) The resulting level of tax is the assumed additional price for that clean energy.

climate change are substantial. Very high SCC values therefore likely indicate that we are far from the optimum, not that it is desirable to use those numbers as effective prices on carbon for regulatory purposes.

A second possible concern with very high values of the SCC, beyond our arbitrary choice of a functional form, is that DICE is based on a growth model that may not be appropriate in cases involving long-term economic decline. If the economy were to contract for a long period of time, the behavior of actors would likely be different than what is assumed in the model. More generally, the model does not contain the flexibility necessary to represent behavior in the wide range of circumstances that climate change might present.

We also note that some choices in DICE may reduce the SCC from its true value. For example, the damage function does not allow for the possibility of a tipping point, where harms accelerate once a threshold is passed (as discussed in, among others, Lenton and Ciscar [2013]; Weitzman [2012]). The damage function in DICE also assumes that goods are perfectly substitutable for one another, so, for example, large reductions in the food supply can be made up for by more televisions. Sterner and Persson (2008) suggest an alternative damage function that includes imperfect substitutability across different types of goods. Models adjusted for these limitations might produce SCC values that are higher even than those shown here. Moreover, if harms to the distant future matter because of low growth rates, the SCC becomes a function of the timescale of the calculation. The IWG's arbitrary choice of a 290-year calculation is not significant when using a fixed several percent discount rate, but with endogenous discounting, a longer timescale would yield larger values in the high-f cases shown here (see online Appendix F). For all of these reasons, the exact numerical values of model estimates of the SCC should be used only with caution.

5. DISCOUNTING

The debate around the proper discount rate to use for estimating the costs of climate change has centered around two positions.[15] One po-

15. The literature on discounting is vast. Useful sources, among many, include Arrow et al. (1996), Nordhaus (2008), Stern (2008), Portney and Weyant (1999), and Lind et al. (1982). Weisbach and Sunstein (2009) summarize the literature focusing on the two positions outlined in the text. The IWG, following Office of Management and Budget guidance, used a fixed discount rate. Neither of the two views on discounting that we discuss support use of a fixed discount rate. Sunstein (2013) justifies the use of a fixed discount rate on the basis of the need to limit discretion by administrative agencies.

sition, sometimes called the descriptive approach (Arrow et al. 1996), views the discount rate as the price of future consumption. For example, if the discount rate is 6 percent, an object that costs \$1 in 12 years can be purchased by saving \$0.50 today. This approach recommends using the market to determine the discount rate, just as the market determines other prices. Prices, including the discount rate, reflect opportunity costs, so failing to use market prices would mean failing to reflect the true costs of future consumption. (In the context of an analysis covering several hundred years, for which there exist no relevant real-world financial instruments, the market discount rate means a rate calculated in a model using a set of parameters calibrated to produce interest rates consistent with observed market rates.)

The other view, sometimes called the prescriptive approach, argues that the consequences of market-based discounting are unethical because with even a modest discount rate, future consumption counts for very close to zero, and the resulting policy recommendations seem to undervalue the future. Parameters derived from observed markets, moreover, might reflect private impatience or the failure of individuals to incorporate the welfare of future people into their private decisions. Because those future people count for social welfare, discounting guided by privately determined market interest rates may not be an appropriate choice for policies that maximize social welfare. As a result, this view suggests choosing parameters that produce a discount rate more consistent with ethical views about the value of future generations. The discounting parameters used in Table 1 were selected to reflect, roughly, these two views.

In standard DICE and most other IAMs, the discount rate used when calculating the present-value costs of climate change is given by the Ramsey equation. If the utility function takes a constant elasticity of consumption form, $U(c) = c^{1-\eta}/(1-\eta)$, the implied market discount rate is $r = \eta g + \rho$, where ρ is the pure rate of time preference (that is, the discount rate on future consumption purely because it is in the future) and g is the growth rate of consumption. As mentioned, those advocating for a market approach to discounting set η and ρ using observable market rates. Discount rates for longer periods of time are then calculated in the model using these assumptions. Those advocating for a discount rate that reflects ethical views often set ρ equal to zero (or a very low number), on the basis that consumption by future people should count the same as consumption by people living today. They often also tend to choose a low value for η, although the basis for this is less clear.

An understanding of the potential interactions between climate change and economic growth can provide some insight into this long-standing controversy. The roots of the dispute may lie not in the principles of discounting but in the fact that model's results are counterintuitive and nontransparent. Imagine someone who believes that climate change is likely to produce terrible harm. A cursory examination of climate harms in a model like DICE might seem consistent with this belief, with climate change reducing output by 10 percent, 20 percent, or even 30 percent, a seeming economic catastrophe. However, the same model, when optimized using market-based discount parameters, suggests that only modest reductions in emissions are warranted. The central reason for the discrepancy may seem to be the high discount rates implied by the model.

This seemingly unethical result is not, however, troubling. It occurs because the model implicitly assumes that growth continues and that future generations are vastly richer than today, notwithstanding what appear to be large harms from climate change. The resulting implied high discount rate is then appropriate, since harms to wealthier future generations should not in fact substantially affect current policies. If climate change negligibly affects future prosperity, there would be little rationale for costly actions to prevent it. If the model instead allowed climate change to affect growth rates, so that future generations were much worse off, the model would produce low (or negative) discount rates. That is, market discount parameters would still tend to support aggressive policies to prevent climate change when those policies are appropriate. The apparently unethical outcome has its origin not in the choice of discount parameters but in the model's implicit and unrecognized assumption of continued growth.[16]

This insight cannot resolve all of the debates about discounting. Nevertheless, we suggest that some who believe that high discount rates produce unethical outcomes are implicitly assuming large harms from climate change while the models used to estimate climate policies assume that possibility away by their very structure. The disconnect between what people assume the models must say and what the models actually produce may explain some of the tension in the debate around dis-

16. In the cases shown in Table 1, the larger the assumed harms to productivity, the more closely the SCC estimates for the two discounting approaches converge (see also online Appendix G).

counting. Once that structure is modified, the centrality of discount rates to climate policy is diminished.

6. CONCLUSIONS

We find that structural assumptions about the interaction of climate change and the economy built into DICE drive its estimates of the SCC. Economic growth in DICE is nearly insensitive to climate change harms and therefore is determined almost entirely by exogenous assumptions about productivity. In the business-as-usual scenario from the 2010 IWG-DICE that we examine, with a mean 1.3 percent/year growth rate, climate harms cause a 0.05 percent/year depression in economic growth, with 0.03 percent/year due to simply the increase in damages over time and only 0.02 percent/year resulting from the internal dynamics of the model. The similarity of SCC estimates across IAMs suggests that this behavior may be relatively common across models. As is well known, over long periods of time exponential growth will dominate all other factors. If climate change has only a negligible effect on growth, it cannot significantly affect consumption levels. To be robust, an estimate of the effects of climate change must also consider more substantial impacts.

This result suggests that SCC estimates are likely far more uncertain than previously recognized, with the uncertainty dominated by the economic effects of climate change rather than by the physics of the climate response. The IWG sampled over a range of climate sensitivities (a key scientific uncertainty) and found a relatively narrow resulting distribution of SCC values, with 95th percentile and central SCC values differing by only a factor of three (\$65/tCO_2 and \$21/tCO_2 for the 2010 SCC in IWG [2010]). Changes to the assumed structure of how climate change impacts the economy produce substantially larger effects (orders of magnitude in Table 1). The uncertainty lies not in the magnitude of climate-related losses at any given time but in how those losses may affect the future. These results suggest that the higher research priority is not quantifying climate harms but understanding how those harms affect growth.

The persistent growth in DICE and other IAMs may underlie some of the tension over choices of discount rates. Since existing models assume that future people will be many times richer than those living today, it should not be surprising that they recommend only modest policies to combat climate change. If this assumption of increasing future wealth is correct, only modest policies would be desirable, and adjusting the discount rate to produce stringent policies would not be appropriate. If, however, climate change means that future people will be worse off than those living today, models can produce high SCC values and recommend stringent policies even with market-based discounting. Debates over discount rates may therefore be clarified if studies are explicit about the level of harms being assumed.

Finally, the large uncertainties in the SCC should not be surprising given the long time frames involved. Predicting economic outcomes over hundreds of years is inherently a difficult exercise even without the introduction of changes to the physical world not previously experienced by modern society. At present, it is not known whether climate change will prove catastrophic or manageable with few impacts. This uncertainty raises questions about how regulatory policy should be made when potential benefits are difficult to compute to within even an order of magnitude. Theories of robust decision making (for example, Gilboa and Schmeidler 1989; Hansen and Sargent 2008) may inform regulators when making policy in the face of potentially large but highly uncertain losses but have only begun to be applied to climate change. While DICE and many other IAMs may assume relatively benign outcomes, the possibility of bad outcomes would likely drive policy under these frameworks.

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Climate impacts on economic growth as drivers of uncertainty in the social cost of carbon

Online appendices

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Contents

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A Standard DICE, IWG-DICE, and the IMAGE scenario

IWG-DICE

IWG-DICE, the model used in the 2010 Interagency Working Group estimation of the SCC, is a modified version of the 2007 release of DICE (Dynamic Integrated Climate-Economy), described in Nordhaus (2007). The IWG made several changes to the model to make it compatible with the IWG process. Those changes are plausible for simulations resembling the business-as-usual trajectory but inappropriate for simulations involving economic decline or substantially reduced economic growth.

First, while standard DICE specifies emissions intensity – the amount of CO_2 emissions that are associated with a unit of economic activity – IWG-DICE specifies fixed emissions pathways which are decoupled from actual economic performance. If the economy in a model simulation declines, retaining a fixed path of emissions implies that people use more energy per unit of output, or that the energy they use is more carbon intensive. In cases of steep economic decline, assumptions of fixed emissions may reverse the sign of implied technological change and imply an increasing rather than decreasing emissions intensity. This result does not appear to be intended by the IWG, and it appears to arise only in scenarios they did not consider. Using exogenous emissions in simulations with economic decline could lead to overestimates of the SCC because CO_2 emissions continue their bascase trajectory (and basecase climate harms) even if the economy contracts. However, in IWG-DICE this effect is largely masked by a compensating error in the carbon cycle, which removes a larger fraction of CO_2 emissions than is physically realistic.(See Appendix E and Glotter et al. (2014)).

Second, while standard DICE uses endogenous discounting, the IWG used a fixed discount rate in their SCC calculations, as required by OMB Circular A-4.

In addition, the IWG fixed the savings rate in the model at 22%. Savings are optimized in the most complete version of standard DICE, though the model is in fact often used with savings rate exogenously fixed instead. The version of DICE we use here and call “standard DICE” has a fixed 22% savings rate. See Appendix E for a test of sensitivity of the SCC to savings rate assumptions.

The IMAGE scenario

Throughout the manuscript we use in examples only one of the five economic scenarios considered by the IWG. The IWG chose five scenarios developed as part of the Stanford Energy Modeling Forum exercise, EMF-22, four them business-as-usual and one an optimistic scenario in which CO_2 is stabilized at 550 ppm. We use the IMAGE scenario, one of the business-as-usual scenarios.

The IMAGE scenario consists of assumed trajectories of three variables: population, CO_2 emissions, and economic output, which in IWG-DICE is translated into an assumed trajectory of productivity. These three assumptions are shown in Figure A.1, along with the emissions intensity that would be implied by them.

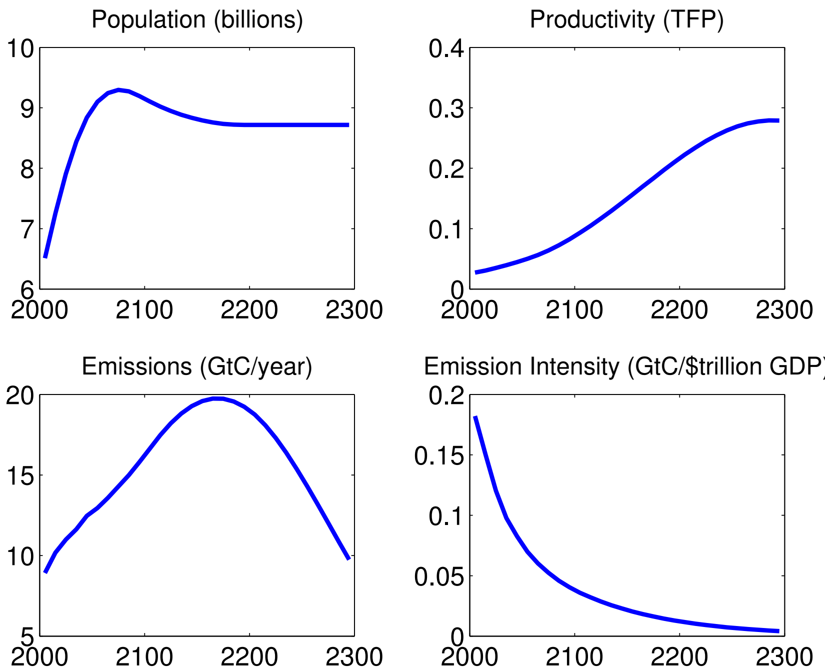

Figure A.1: Assumptions of the IMAGE scenario used by the IWG, and emissions intensity implied by assumed economic output and CO_2 emissions.

In the IMAGE scenario, CO_2 emissions increase for ∼150 years and decline thereafter, presumably driven by some assumed technological change. By the end of the scenario period, emissions have returned to near present-day values. We take no position on the plausibility of the emissions pathway, which implies that CO_2 emissions would decline steeply (and emissions intensity drop by a factor of over 30) even in the absence of mitigation policies. Cumulative CO_2 emissions over the 300-year scenario are equivalent to ∼4,600 GtC (billion tons of carbon, not carbon dioxide), similar to estimates of global available fossil carbon.

B IWG SCC estimates from 2010 and 2013

The paper analyzes the social cost of carbon calculations from the initial IWG report, released in March 2010 (IWG, 2010). In May 2013 the IWG released an updated set of SCC estimates (IWG, 2013). The IWG recalculated SCC values using updated versions of all three IAMs used in the original study (DICE, FUND, and PAGE), based on new code releases by the models' original authors. Changes to the three models are summarized below. The IWG did not make any changes regarding the discount rates, the basecase economic scenarios (economic growth, population, and emissions), or the distribution of climate sensitivities.

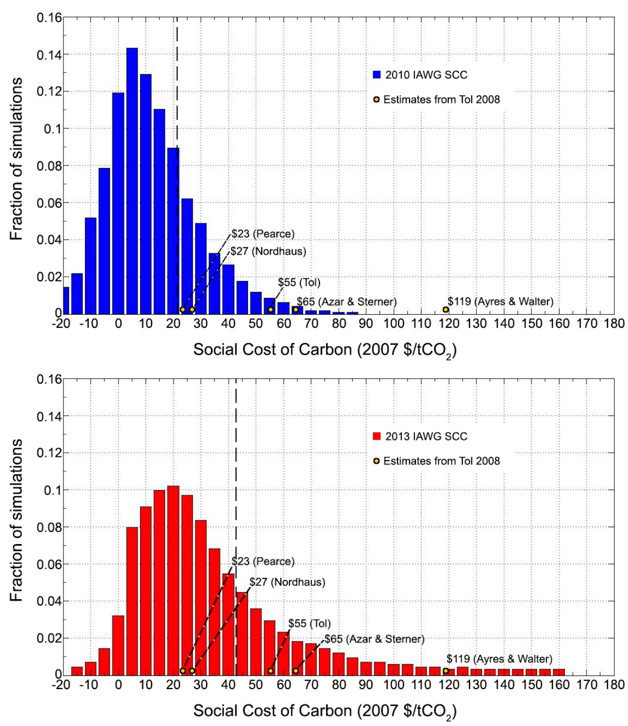

Figure B.1: Comparison of SCC distributions from the 2010 and 2013 IWG reports with a 3% discount rate. Distributions sample across socioeconomic scenarios and climate sensitivities. Top: 2010 IWG SCC estimates for year 2010 (repeats manuscript Figure 3 in color). Bottom: 2013 IWG SCC estimates for year 2020. Dashed lines show mean values for each distribution. Values are digitized from Figure A8 of IWG (2010) and from an un-numbered figure on p. 14 of IWG (2013). Original data are no longer available.

Comparing SCC estimates between the two studies is complicated because the SCC grows over time and the IWG reported values largely for the year 2010 in the original report but for the year 2020 in the update. In the original report, SCC values grow by ∼20% between 2010 and 2020. The new report provides a distribution of 2020 SCC estimates in which the central and 95th percentile estimates are roughly 60% higher than the original 2010 values (Figures B.1 and B.2), suggesting a moderate real increase in estimated SCC values. The change does not qualitatively impact the conclusions and recommendations of this study.

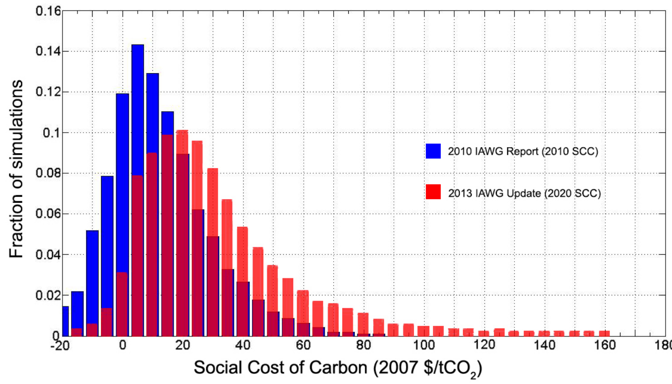

Figure B.2: Superimposed SCC distributions from the 2010 and 2013 IWG reports for the 3% discount rate case. Data sources as in Figure B.1 Note that SCC estimates are for different years (2010 and 2020).

Changes to individual models are described below. Because the SCC is an average of the outputs of all three IAMs, all model changes impacted the reported SCC estimates.

DICE updates

IWG-DICE was updated to reflect changes that appeared in the 2010 version of standard DICE. Changes included a damage function that represents sea level rise separately from all other damages and adjustments to the carbon cycle representation.

The carbon cycle model in the 2010 version of DICE is based on the same set of linear equations as the 2007 version, but uses a revised set of parameters. In both versions, parameter values were calibrated against more complex models. The choice of parameters in 2010 DICE decreases CO_2 uptake by the ocean, leaving a higher fraction of emitted CO_2 in the atmosphere and therefore producing higher temperature anomalies and larger climate harms. See Glotter et al. (2014) for a comparison of the two carbon cycle versions. The changes in 2010 DICE do not prevent the excessive long-term uptake rates discussed in Appendix E and Glotter et al. (2014), which result from failure to incorporate nonlinear ocean chemistry.

The new DICE damage function decomposes harms into two parts: one specific to sea level rise and one representing all other harms. Each of these component damage functions models economic harms as a quadratic function of temperature change, as in the 2007 version. According to IWG (2013), the effect of the change to the damage function is to increase overall harms slightly in the short-run, decrease them in the medium-term, and increase them in the long-term. After discounting, the impact of this revision is to decrease the SCC.

FUND updates

The FUND model was revised to reflect new features in version 3.8. Changes include revised damage functions for sea level rise, the agricultural sector, and space heating demand; adjusted speed of temperature response to increased GHG concentrations; and addition of indirect effects of methane emissions.

PAGE updates

The PAGE model was updated based on the 2009 model version. Changes include a separate representation of harms from sea level rise, an upper bound on the magnitude of harms, a revised method for scaling harms at the regional level, a probabilistic treatment of passing a climate threshold beyond which society suffers extreme economic harms, and revised assumptions about the rate and magnitude of adaptation to climate change.

C Comparison: standard DICE, IWG-DICE, FUND

To test whether persistent economic growth in IWG-DICE is the result of the IWG's modifications, we compare IWG-DICE with standard DICE and FUND (Figure C.1). All models show similar behavior, with economic growth insensitive to climate harms despite temperature rise of 6–9° C.

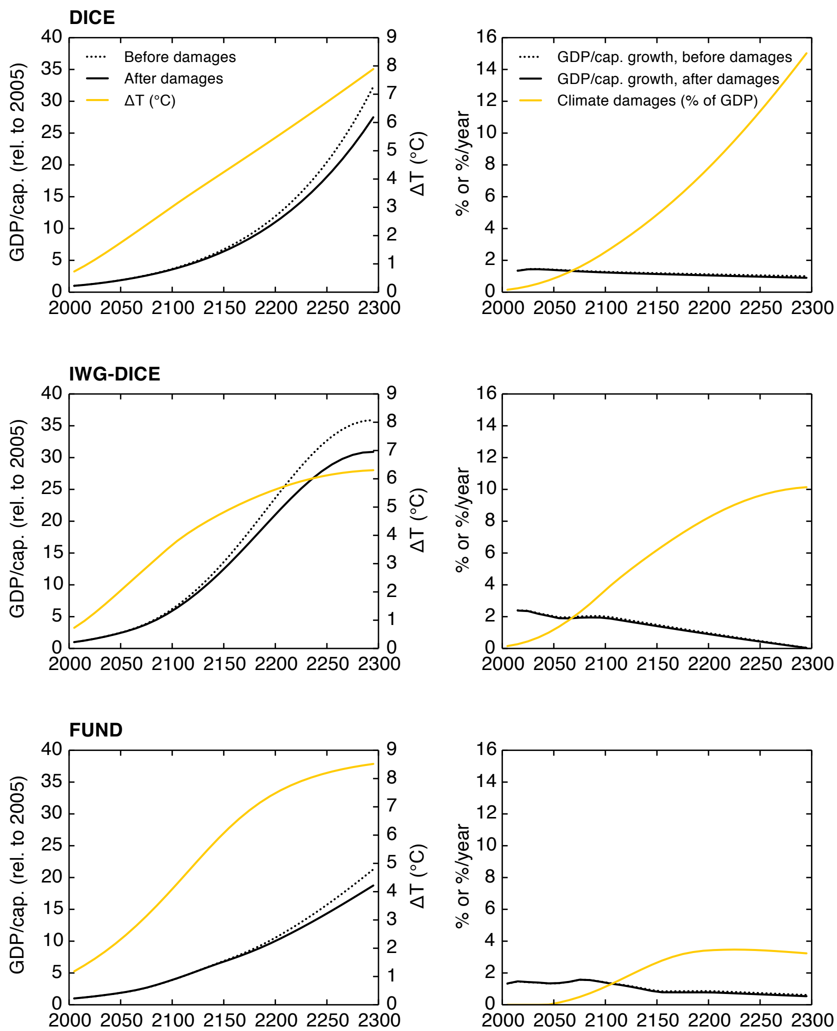

Figure C.1: Comparison of behavior across models. Left: T increase (relative to pre-industrial) due to CO_2 emissions and economic output with and without resulting harms. Right: climate harms (% of output) and economic growth (%/year) with and without those harms. See Appendix A and manuscript for model descriptions. In standard DICE, we have disabled the model cap on cumulative emissions. FUND assumes net benefits for moderate climate change, but net harms after 2050.

D DICE dynamics and growth accounting

The structure of IWG-DICE inherently limits the ability of climate change to alter economic growth. In this section, we review the mathematics that underlie the insensitivity of IWG-DICE to harms from climate change and determine the relative importance of the factors affecting growth in the IMAGE scenario.

D.1 Equivalence to basic growth model

The economic core of IWG-DICE is a Solow-Swan growth model with a Cobb-Douglas production function, modified so that output is reduced by harms from climate change. In a continuous time representation, output is:

$$Y = (1 - D) \cdot A \cdot L^{1-\alpha} \cdot K^{\alpha} \tag{1}$$

where Y is the rate of output production (\$/time), D is the fractional loss of output due to climate change, A is total factor productivity, L is labor (population) and K is capital. In per capita units:

$$y = (1 - D) \cdot A \cdot k^{\alpha} \tag{2}$$

where $y = Y/L$ and $k = K/L$ are per capita output and capital, respectively. Capital then evolves in response to savings and depreciation according to the fundamental Solow-Swan equation.

In IWG-DICE, all variables other than output and capital are specified exogenously: population L is prescribed in the scenario being modeled; productivity A is specified to match the scenario base case output; and CO_2 emissions are prescribed, which means that harms from climate change D are exogenous to the economic model. IWG-DICE is therefore identical to the standard Solow-Swan model, only with A replaced by $(1 - D) \cdot A$.

The equivalence with the standard Solow-Swan model provides insight into the degree by which climate change affects growth in IWG-DICE. In the Solow-Swan model, if an economy evolves along a balanced growth path (steady population and productivity growth, so that capital and output maintain a fixed ratio), per capita output growth is constant and equal to the growth rate in $A^{1/(1-\alpha)}$. If IWG-DICE met these conditions, its growth rate would equal that in $[(1 - D) \cdot A]^{1/(1-\alpha)}$.

The identical mathematical treatment of A and $(1-D)$ underlies the persistence of growth even under the extreme assumptions, as shown in manuscript Figure 1 (also Figure E.1), where climate-related harms destroy more than 70% of economic activity by the end of the simulation. (That is, the damage factor $(1 - D)$ drops by factor of three to 0.3). Those harms are outweighed by the fact that productivity A rises by a factor of ten. On a balanced growth path, for the economy to shrink, climate-related harms would have to destroy over 90% of output.

The specific contribution of climate harms to growth under balanced growth equals the growth rate of $(1 - D)^{1/(1-\alpha)}$. Climate harms would therefore reduce annualized growth in year t by $(1 - D_t/1 - D_0)^{1.43/t} - 1$. In the 290-year IWG-DICE / IMAGE simulation, climate harms due to accumulated atmospheric CO_2 rise from negligible to 10% of economic output. Their expected growth impact is then $\left(0.9^{1.43/290}\right) - 1 = .052\%$/year. This value is exactly that found by comparing simulations with and without climate harms. Although the economy in the IMAGE scenario does not evolve on a balanced growth path, the framework nevertheless has explanatory power.

The balanced-growth perspective is useful because although the growth rate in IWG-DICE / IMAGE does evolve over the simulation period, the slowness of that evolution simplifies the model dynamics and allows model behavior to be approximated with an analytical expression. In the following sections we describe the derivation of that expression (following standard discussions of balanced growth), show that it reproduces numerical simulations of IWG-DICE / IMAGE, and use it to quantify the various factors contributing to long-term growth in the model.

D.2 Quasi-balanced growth (QBG)

The dynamics of the Solow-Swan model (Equation 2) lie in the response of capital to changes in exogenous parameters. If capital were fixed, any change in productivity or climate harms (which we collectively denote as $C_d \equiv (1 - D) \cdot A$) would produce only an immediate proportional change in output: $y_1/y_0 \propto C_{d_1}/C_{d_0}$. We term this instantaneous response the "direct" effect of changes in productivity or climate harms. Over time, because changes in output affect savings, capital grows or declines in response to changes in C_d, amplifying the "direct" effect. We term this slower response the "indirect" effect of changes in productivity or climate harms.

If the growth rates in C_d and in population (g and n) were constant[1], then capital-to-output ratio would stabilize at a fixed value that we denote as C_k:

$$\left(\frac{k}{y}\right)_{bg} \;=\; \frac{s}{(\delta + n + g)} \;\equiv\; C_k \tag{3}$$

Combining Equations 2 and 3 yields the expression for evolution of output under balanced growth[2]:

$$y_{bg} \;=\; (C_d \cdot C_k^{\alpha})^{1/(1-\alpha)} \tag{4}$$

IWG-DICE / IMAGE does not follow balanced growth because although savings s and depreciation δ are fixed, g and n change over time. Both slow to

[1] g and n are the fractional rates of change in C_d and L, respectively. On the balanced growth path, g is also the growth rate in per capita output.

[2] Equation 4 is the solution of

$$y = C_d \cdot k^{\alpha}$$
$$y = (1/C_k) \cdot k$$

essentially zero by the end of the simulation, raising the balanced-growth capital-to-output-ratio C_k from 2.2 to 3.4 years.[3] However, the model's dynamics are simplified because the timescale over which this change occurs is slow relative to the timescale on which capital adjusts.[4] Capital and output can then be approximated as reaching their balanced-growth ratio at each point in time. Under these conditions Equation 4 still holds, but C_k becomes, like C_d, a time-dependent variable that evolves slowly. We term this simplification the "quasi-balanced-growth" (QBG) approximation, by analogy with the well-known quasi-steady-state approximation used in analyzing dynamical systems.[5]

The quasi-balanced-growth approximation reproduces IWG-DICE / IMAGE behavior extremely well, barring a few decades at the beginning of the simulation (Figure D.1). During that early period output is depressed below that expected on the quasi-balanced-growth path, because capital and output are initialized out of balance, at 23% and 7% below their respective balanced-growth values. This imbalance lessens quickly, since the timescale for adjustment of capital is only $\tau_k \sim 20$ years (see footnote 4). We can include this "rebound" effect in Equation 4 by multiplying the right-hand side by a term that describes the lessening imbalance as the system comes into QBG evolution: $1 + \mathrm{e}^{-t/\tau_k}\left(y_0/y_{0_{bg}} - 1\right)$. With the rebound effect included, the QBG solution captures output in IWG-DICE / IMAGE to within 2% at all times (Figure D.1).

D.3 Growth accounting in IWG-DICE / IMAGE

The analytical solution for quasi-balanced-growth can be decomposed into the different factors that affect long-term growth rates. Using Equation 4 and the rebound term, the change in output between years 0 and t can be written as:

$$\frac{y_t}{y_0} = \underbrace{\left(\frac{C_{d_t}}{C_{d_0}}\right)}_{\text{“Direct”}} \cdot \underbrace{\left(\frac{C_{d_t}}{C_{d_0}}\right)^{\alpha/(1-\alpha)}}_{\text{“Indirect”}} \cdot \underbrace{\left(\frac{C_{k_t}}{C_{k_0}}\right)^{\alpha/(1-\alpha)}}_{\text{“Capital-to-output ratio”}} \cdot \underbrace{\frac{y_{0_{bg}}}{y_0}}_{\text{“Rebound”}} \tag{5}$$

provided the system has reached QBG by year t. The first two terms capture the effects of changes in productivity or climate harms discussed in section D.1. The

[3] When using Equation 3, the parameters specified in the DICE code must be adjusted. In DICE, which uses 10-year timesteps, depreciation and savings are treated differently: depreciation is compounded but savings are a specified fraction of output over each 10-year period. The 10-year savings in period i are $10 \cdot s \cdot y_i$, but the 10-year depreciation is $\left(1 - (1-\delta)^{10}\right) \cdot k_i$. The DICE depreciation rate of 10%/year ($\delta = 0.1$) is analogous to a non-compounded rate of 6.5%/year ($\delta = 0.065$). n and g must be specified consistently with d and s.

[4] The timescale for adjustment of capital is $\tau_k = ((1-\alpha) \cdot (\delta + n + g))^{-1}$ (see Barro and Sala-i-Martin (2004) p. 58 for derivation). In IWG-DICE / IMAGE, $\tau_k \sim$ 15–20 years, but C_k rises by ∼50% over 290 years, implying a timescale of nearly 700 years.

[5] The quasi-steady-state approximation is a method for simplifying systems of differential equations involving several different timescales by assuming that the most rapid process goes to its steady-state value. Some economists use the term quasi-steady-state differently, to describe stochastic variation around a steady state (e.g. Acemoglu (2009) p. 570).

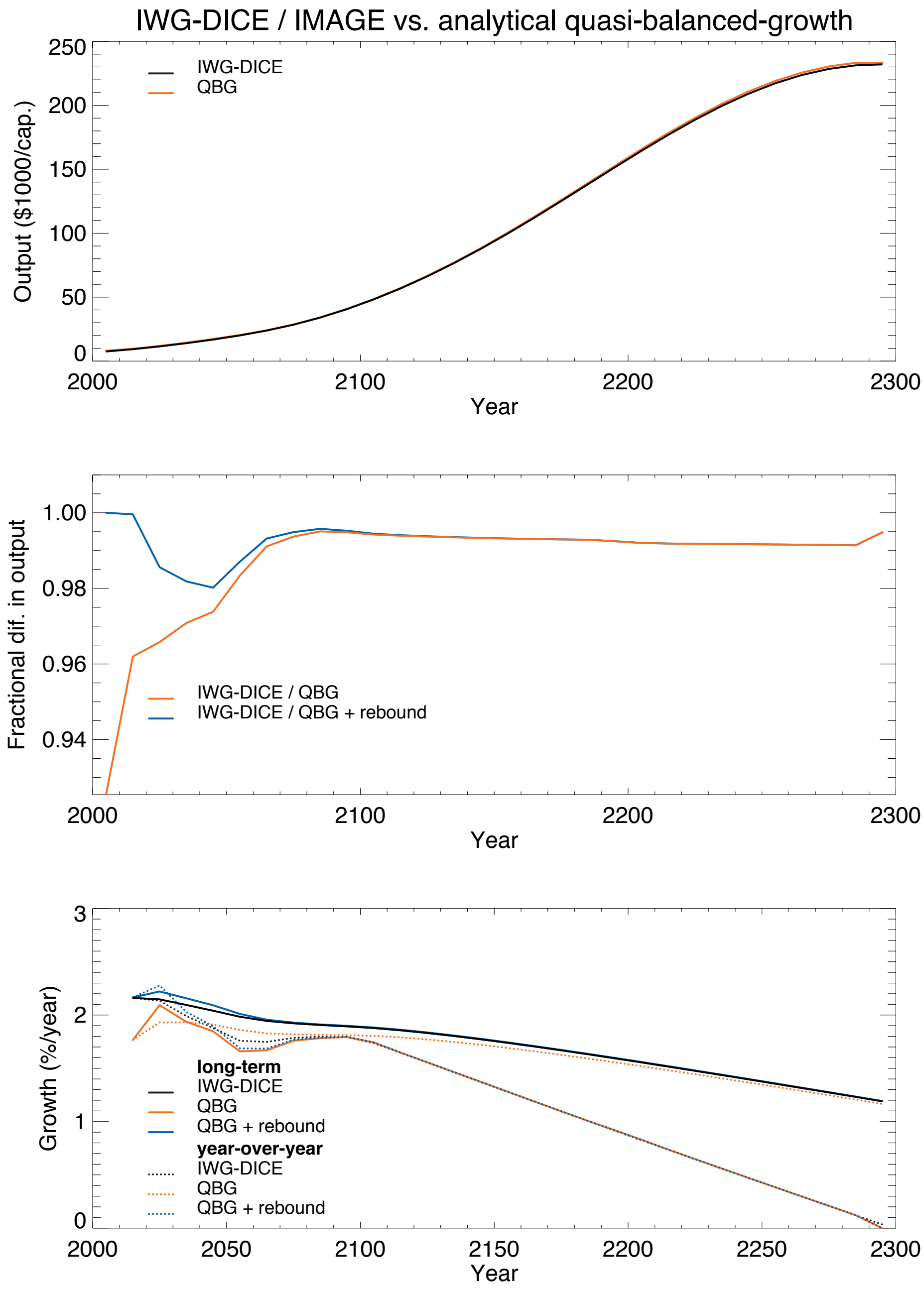

Figure D.1: Top: comparison of IWG-DICE / IMAGE (black) with quasi-balanced-growth (QBG) analytical solution (red). C_k is calculated by taking g as the growth rate of per capita output. The final 200 years of the IWG-DICE / IMAGE simulation are essentially pure QBG. Middle: fractional comparison, now also showing QBG solution with inclusion of "rebound" from initial imbalance (green), as described in text. With the rebound term, the analytical expression reproduces model output to within 2% at all times. Bottom: both year-over-year and long-term growth rates in IWG-DICE / IMAGE are well-described by QBG.

first term is the instantaneous "direct" effect, assuming no change in capital, and the second is the indirect amplification of that effect as capital adjusts. Because the capital share of output, α, is only 0.3, capital amplification is always smaller than the direct effect driving it. (The capital response increases any direct effect on growth rate by an additional factor of $\alpha/(1-\alpha) = 43\%$.) The third term results from the slowly evolving capital-to-output ratio C_k. Finally, the last term describes the recovery from unbalanced initial conditions. In summary, the first two terms describe balanced growth, the third must be added if the economy evolves instead under quasi-balanced growth, and the last must be added if a simulation is initialized out of balance.

We estimate the contributions of these individual terms to the long-term annualized growth rate in Table D.1 below (breaking out the direct and indirect effect of changes in productivity A and climate harms $(1-D)$ separately). To demonstrate the validity of the QBG approximation, we also show estimates for each term derived by comparing model runs with individual parameters fixed or evolving. The growth effects calculated from the QBG expression are essentially identical to those determined empirically from model runs, demonstrating again that the QBG approximation provides useful insight into model behavior.

<table>
<tr><th rowspan="2">%/year</th><th colspan="2">A</th><th colspan="2">$1-D$</th><th rowspan="2">C_k</th><th rowspan="2">rebound</th><th rowspan="2">total</th></tr>
<tr><th>direct</th><th>indirect</th><th>direct</th><th>indirect</th></tr>
<tr><td>Model</td><td colspan="2">1.15</td><td colspan="2">-0.052</td><td colspan="2">0.088</td><td>1.19</td></tr>
<tr><td rowspan="2">QBG</td><td colspan="2">1.16</td><td colspan="2">-0.052</td><td colspan="2">0.090</td><td rowspan="2">1.20</td></tr>
<tr><td>0.81</td><td>0.35</td><td>-0.036</td><td>-0.016</td><td>0.063</td><td>0.027</td></tr>
<tr><td>QBG y_r</td><td>$\frac{A_{290}}{A_0}$</td><td>$\frac{A_{290}}{A_0}^{.43}$</td><td>$\frac{1-D_{290}}{1-D_0}$</td><td>$\frac{1-D_{290}}{1-D_0}^{.43}$</td><td>$\frac{C_{k290}}{C_{k0}}^{.43}$</td><td>$\frac{y_{0_{bg}}}{y_0}$</td><td></td></tr>
</table>

Table D.1: Contributions to long-term growth rate in IWG-DICE / IMAGE, in %/year, determined both from model runs ("Model") and from the analytical QBG approximation ("QBG") using expressions given in the last table row. Output ratios y_r are converted to an annualized growth rate via $g = {y_r}^{1/290} - 1$ and rounded to two or three significant figures. "Model" growth effects from changes in A or $(1-D)$ are determined by comparing y_{290}s in the baseline run and in a run with the relevant parameter fixed, and the combined growth effect from changes in C_k and from rebound by comparing y_{290} to y_0 in a run with A and D both fixed. The total "Model" growth rate of 1.19%/year is identical whether taken from the total change in the baseline run or by summing individual components. The initial balanced-growth output would be $y_{0_{bg}} = (A_o(1-D_o)/C_{k_o}^{0.3})^{1.43}$.

The discussion above is intended to clarify the intrinsic limits of a Solow-Swan-type model in representing potential negative impacts of climate change. While the magnitude of climate harms on output in IWG-DICE / IMAGE is in line with literature estimates (IPCC, 2007), those harms produce only a slight reduction in long-term growth. That result is not a finding but is engrained in model assumptions. The behavior of the economy is dominated by the assumed order-of-magnitude future growth in productivity, which far outweighs climate harms.

However, it is interesting to note that per capita output in IWG-DICE / IMAGE would grow in the face of climate change even if there were no *future* productivity growth (i.e. even if A were fixed at its initial value throughout the simulation), because of the repercussions of *past* growth in a slowing economy. The IMAGE scenario is initialized with realistic economic and population growth and with capital and output near their balanced-growth ratio, presumably reflecting several prior decades of evolution in similar conditions. As growth slows and the economy comes into steady state ($n = 0, g = 0$), the balanced capital-to-output ratio C_k rises, producing a corresponding 20% rise in per capita output.[6] But climate harms in IWG-DICE / IMAGE reduce output directly only by 10%, with an additional 4% from indirect amplification. The expected rise in per capita output from a slowing economy outweighs the full harms of unmitigated climate change.[7]

[6]The C_k effect is identical regardless of whether productivity A first grows and then stabilizes, or whether A is fixed at its initial value, i.e. slows its growth immediately. The final steady-state capital-to-output ratio is the same in both cases.

[7]If atmospheric CO_2 and resulting climate harms continued to increase over time, they would at some point outweigh the C_k effect, so statements about the relative importance of the two terms would depend on the simulation timescale. However, in both IWG-DICE / IMAGE and standard DICE, cumulative CO_2 emissions are capped, so maximal climate harms are indeed roughly 10% of output. (See Appendix A. In Figure C.1 we lifted this cap for standard DICE.) In Table D.1 we show the joint effects of slowing g and n, but the C_k effect would outweigh that of climate harms even if population growth n remained constant. The C_k effect has relevance beyond IWG-DICE / IMAGE. A similar rise will be realized in any economic simulation that is initialized reflecting realistic conditions and is extended to a time period when growth in output and population have slowed to nearly zero.

E Factors influencing the SCC

Treatment of harms

We have shown that in IWG-DICE, even unrealistic levels of harm do not cause net economic contraction, and (Figure E.1, left) significant growth effects occur only if harms are allowed to impact productivity (Figure E.1, right). In the case with harms at 2.5°C calibrated to 30% of output, harms exceed 70% of output by 2300, but growth remains positive. By contrast, even a small fraction of harms assumed to affect TFP causes economic decline and would, over sufficient time, produce net economic contraction.

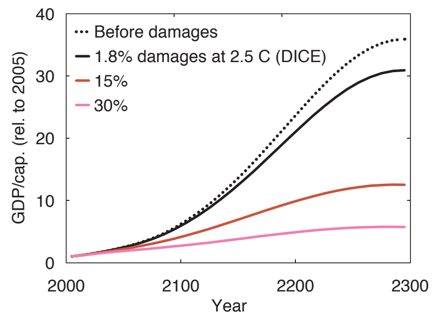

Figure E.1: Sensitivity of IWG-DICE economic output to the magnitude of assumed harms (left) and to the fraction of harms that affect productivity (right). Left and right panels repeat manuscript Figures 1 and 2, respectively.

Carbon cycle

While the IWG scenarios prescribed trajectories of CO_2 *emissions* (tons/year), climate change and climate harms depend on CO_2 *concentration*, i.e. on the total amount of CO_2 in the atmosphere. If all human-produced CO_2 were retained in the atmosphere, then concentration would simply increase with cumulative emissions. However, human-produced CO_2 perturbations decay over time in a complex manner, and uptake of CO_2 by the ocean must be modeled with a separate "carbon cycle". The accuracy of a model's carbon cycle representation can thus strongly affect climate harms and therefore estimated SCC values.

The carbon cycle in standard DICE and IWG-DICE provides physically realistic ocean uptake only for several decades. At longer timescales, it deviates strongly from the predictions of state-of-the-art coupled climate models, removing CO_2 too quickly. In DICE, human-produced CO_2 perturbations disappear entirely within a few centuries, while in more physically realistic models, about half the emitted CO_2 persists for thousands of years (e.g. Archer et al., 2009).[8] Analyses over longer time periods, such as the IWG's 290 years, can therefore be biased, since lowered atmospheric CO_2 produces lowered climate harms and in turn lowered cost estimates.

[8] Adjustment of the carbon cycle parameters in the 2010 DICE update used in IWG (2013) does not fix the problem of excessive long-term CO_2 uptake.

Errors in CO_2 evolution arise in DICE because the model uses a linear representation of ocean carbon uptake, while in the real world, ocean carbonate chemistry makes uptake nonlinear. At present, the ocean contains far more dissolved inorganic carbon than would be indicated by the solubility of CO_2 itself, primarily in the form of bicarbonate (HCO_3^-) and to a lesser degree carbonate ($CO_3^=$). As the ocean acidifies in response to CO_2 uptake, the partitioning shifts toward CO_2, reducing the oceans' ability to store carbon and slowing uptake (Revelle and Suess, 1957). Since the DICE carbon cycle does not include this nonlinear chemistry, it produces too-rapid removal of atmospheric CO_2 perturbations. To correct this problem, we use the simple carbon cycle model known as "BEAM" or the Bolin and Eriksson Adjusted Model (Glotter et al., 2014), which is based on Bolin and Eriksson (1959) with nonlinear chemistry as described in Revelle and Suess (1957).[9]

The use of the more physically realistic BEAM produces substantial changes in CO_2, temperature anomalies, and SCC estimates (Figure E.2 and Table E.1). Long-term CO_2 concentrations nearly double, leading to an additional $\sim 2°C$ of warming.[10] With the standard DICE function for climate damages, substituting the BEAM carbon cycle roughly doubles SCC values. The accuracy of the long-term climate representation can become still more important if climate harms are large enough to substantially reduce economic growth and produce large negative discount rates. When climate harms strongly affect productivity, under high discount parameters the use of BEAM can increase SCC estimates by more than a factor of five (Table E.1).

Treatment of harms	$\eta = 2, \rho = 1$ *"descriptive"*			$\eta = 1, \rho = 0$ *"prescriptive"*		
	DICE	BEAM	ratio	DICE	BEAM	ratio
Unmodified	16	29	1.8	120	270	2.2
1% to TFP	21	34	1.6	270	540	2.0
5% to TFP	41	75	1.8	770	1500	2.0
10% to TFP	71	150	2.1	1300	2500	2.0
25% to TFP	200	1100	5.5	2500	5100	2.1
50% to TFP	610	3800*	*NA*	3800	5800*	*NA*

Table E.1: 2010 SCC values (2007\$/tCO_2) from standard DICE with and without substitution of BEAM for the DICE carbon cycle model. Table is similar to manuscript Table 1 and repeats most values, adding only the "prescriptive" BEAM case for comparison. In starred cases, calculation of the SCC is truncated when the economy reaches subsistence level. (See Section G for comparison of truncated and non-truncated values.) Carbon cycle accuracy matters most when future harms are large and discount parameters are high.

[9] We use the version of BEAM omitting the temperature dependence of solubility and partitioning coefficients.

[10] We show here examples using standard DICE rather than IWG-DICE to avoid the unphysicality of the exogenous emissions in IWG-DICE. (See Appendix A for discussion.)

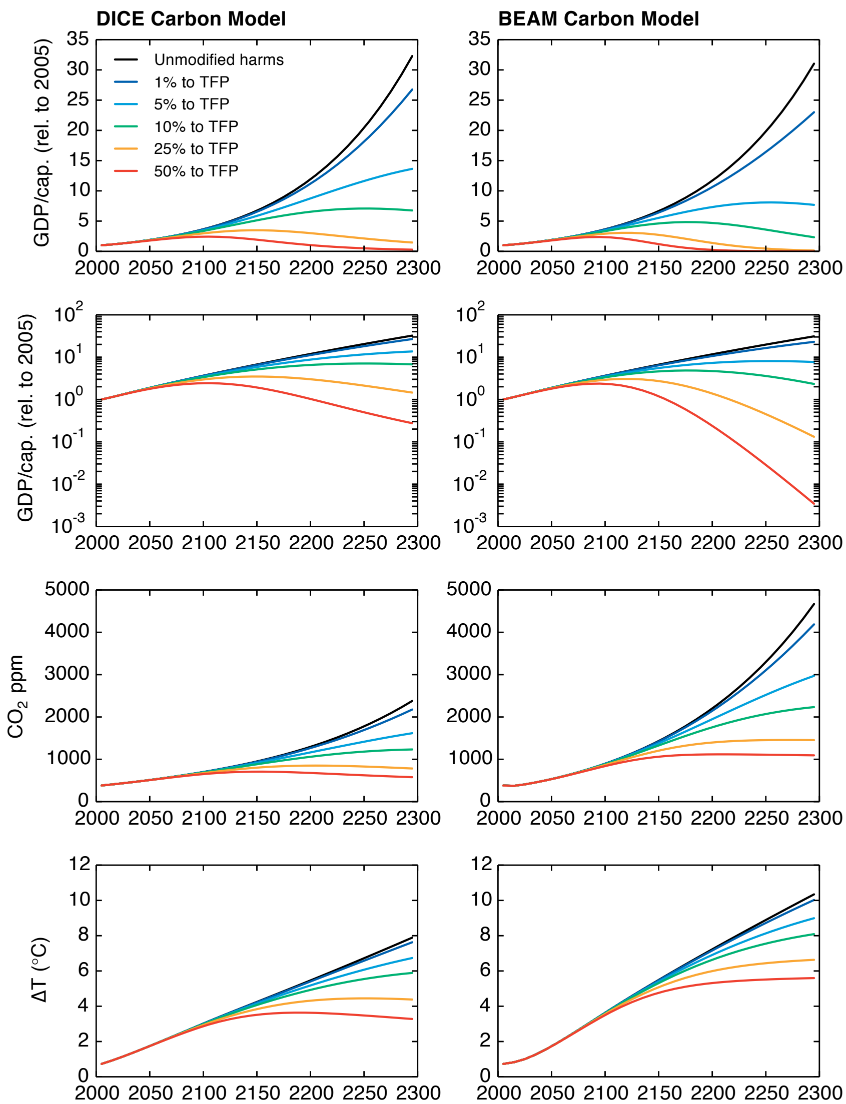

Figure E.2: Comparison of standard DICE with and without substitution of BEAM for the DICE carbon cycle model. (For this purpose we have disabled the model cap on cumulative emissions.) Use of BEAM roughly doubles long-term CO_2 concentrations, providing an additional 2°C of warming. At high damages to productivity, additional climate harms reduce per capita GDP by orders of magnitude. The worst-case trajectory here falls below the subsistence level of ∼\$250/capita/year ($\sim 3 \cdot 10^{-2}$ times present-day per capita output). Note that temperature change in DICE is benchmarked from the pre-industrial, so the initial year 2005 has already experienced ~ 0.8°C global temperature rise.

Savings rate

We have shown above that the SCC is highly sensitive to treatment of climate harms and the carbon cycle. We need to test as well whether the SCC is *insensitive* to another model assumption, that of fixed savings. The constraint of fixed savings in IWG-DICE means that individuals cannot alter their savings rates in response to impending economic collapse. To understand the scale of potential savings rate effects, we repeat some model runs with higher and lower savings rates, and find that these changes do not qualitatively alter results.

Using standard DICE, we test the effect of savings rates of 15%, 22%, and 30% in the case of moderately high ($f = 25\%$) impact of climate harms on productivity (Table E.2). These savings rate choices can alter SCC values by $\sim 20\%$ (a factor of 1.2), but this change is small relative to that resulting from altering the damage function: setting $f = 25\%$ raises SCC values by factors of 12 and 20 over the baseline ($f = 0\%$) case for high and low discount parameters, respectively.

Savings rate	$\eta = 2, \rho = 1$ *"descriptive"*	$\eta = 1, \rho = 0$ *"prescriptive"*
15%	240	2800
22%	200	2500
30%	160	2100

Table E.2: 2010 SCC values (2007\$/tCO_2) from standard DICE (with standard carbon cycle) with 25% of damages applied to TFP, for three different exogenously fixed savings rates.

F Impact of time horizon of calculation

Since the SCC is intended to represent the present-value sum of all future climate harms, and anthropogenic CO_2 should persist in the atmosphere for thousands of years, the finite (290 year) length of the IWG's simulations can artificially limit resulting SCC values. We test here the effect of altering the time horizon on SCC estimates, using 600-year runs of standard DICE with both DICE and BEAM carbon cycles and with various specifications of climate harms. (See Figure E.2 for simulations used). We then calculate SCC values from output truncated at 100, 200, 300, and the full 600 years.

In general, SCC values increase monotonically with both the degree of climate impact on productivity (f) and with the time horizon considered. A 300-year time horizon is sufficient to produce relatively stable SCC estimates only in certain cases, most clearly when using high discount parameters and the DICE carbon cycle (Figure F.1, top left). A longer time horizon affects SCC estimates more strongly when using low discount parameters (because the future tends to be weighted more), or the BEAM carbon cycle (because climate harms in the 300-600 year period are larger) (Figure F.1, bottom row and right column, respectively).

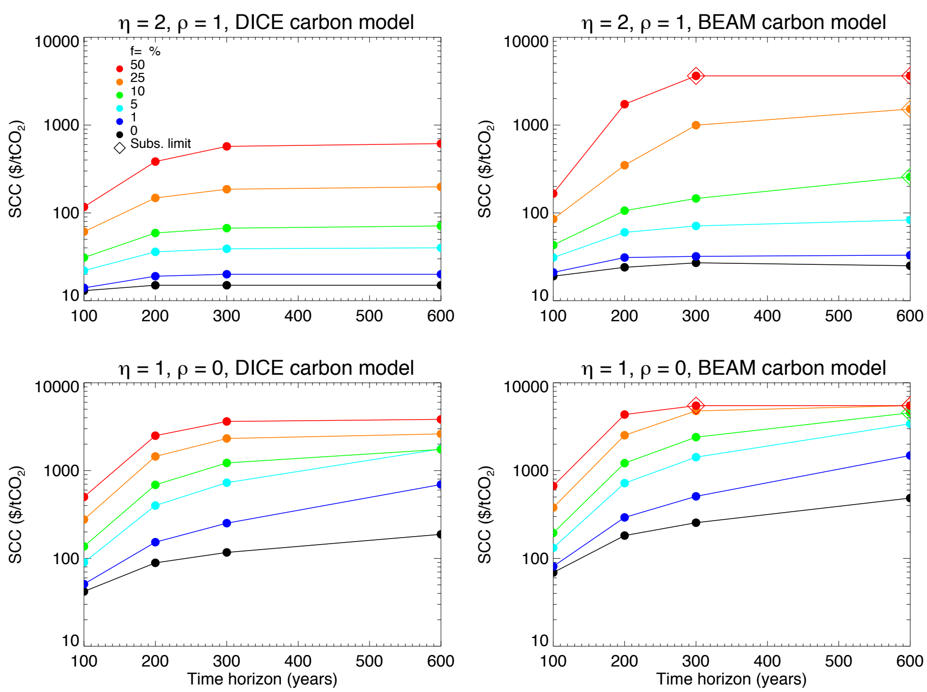

Figure F.1: Impact of time horizon choice (100, 200, 300, or 600 years) on SCC values, for the standard DICE runs shown in Figure E.2. Datapoints marked with diamonds are those where per capita output falls below subsistence level and we disallow any further increases in the SCC.

Extending the time horizon to 600 years has relatively little effect in cases with high fraction of damages to TFP, largely because in these simulations the economy has contracted strongly already by year 300. Because CO_2 emissions are endogenous, emissions effectively cease and climate harms then decrease (because of ocean uptake) rather than increase over time. With the BEAM carbon cycle, economic contraction is so severe that the per capita output drops below subsistence level and we truncate any further increases in the SCC.

The general patterns described above are seen more clearly in plots of the relative change in SCC values for these cases (Figure F.2). The relative effect of extending the time horizon is largest for low discount parameters or when BEAM is substituted for the DICE carbon cycle. In these cases the SCC can triple when estimated at 600 rather than 300 years.

We present these examples as an exercise in understanding model behavior, not as meaningful quantitative predictions. Note that some of these simulations become unphysical if extended, since we have disabled the DICE cap on cumulative emissions. In the low-damages cases, humanity at year 600 has burnt more than the total estimated global fossil carbon reserve.

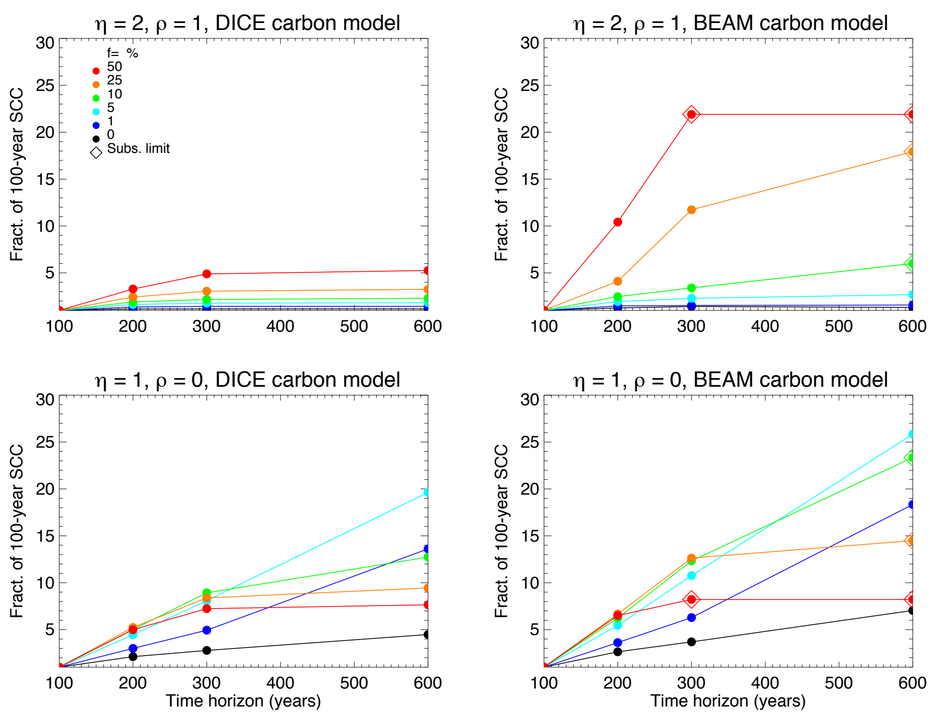

Figure F.2: Relative change in SCC values for extending the time horizon from 100 to 200, 300, or 600 years, in the standard DICE runs shown in Figures E.2 and F.2. Again, datapoints marked with diamonds are those where per capita output falls below subsistence level and we disallow any further increases in the SCC.

G Impact of discount parameters when climate harms are large

Throughout this discussion we have shown examples of the SCC calculated in standard DICE using two sets of discount parameters to calculate an endogenous discount rate via the Ramsey equation:

$$r_t = \eta \cdot g_t + \rho, \tag{6}$$

where η is the elasticity of the marginal utility of consumption, g_t is the growth rate in the economy, and ρ is the pure rate of time preference (i.e., the discount rate applied to utility for purposes of social welfare maximization). We consider the two cases $\eta = 2, \rho = 1$ ("descriptive") and $\eta = 1, \rho = 0$ ("prescriptive").

In the IWG-DICE / IMAGE basecase, using "prescriptive" parameters yields lower discount rates and therefore higher SCC estimates: the future is weighted more heavily. If growth rates were always negative, the "descriptive" discount parameters would place greater weight on future harms. In our simulations, as we increase the fraction of climate harms that affect productivity, producing longer periods of economic decline, the relative effects of the two discounting cases should switch. That crossover point occurs at $f \sim 0.4$ (Figure G.1). For "descriptive" discount parameters, SCC estimates rise exponentially with the fraction of climate harms that affect productivity. However, simulations at high f involve economies declining past the minimum threshold for human subsistence. If we truncate SCC estimates at the subsistence threshold, SCC estimates are always higher with "prescriptive" discounting, but the distinction becomes less important as economic impacts increase.

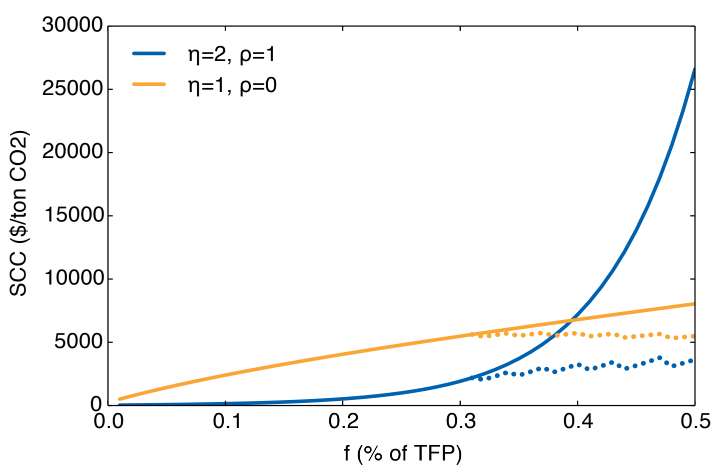

Figure G.1: Estimated SCC values in IWG-DICE / IMAGE for varying values of f. Solid lines show values calculated from entire timeseries; dashed lines show estimates truncated when economies decline to output of \$250/capita/year.

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