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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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Marinescu, Alex Marten, Gilbert Metcalf, Nicholas Stern, Martin Weitzman, and participants at seminars at the University of Chicago Law School and the University of Pennsylvania Law School for helpful comments. Joe Zhu digitized the 2010 and 2013 social cost of carbon (SCC) estimates from Interagency Working Group on Social Cost of Carbon (IWG) reports. This research was performed as part of the Center for Robust Decision Making on Climate and Energy Policy at the University of Chicago, funded by a grant from the National Science Foundation (NSF) Decision Making under Uncertainty program (no. SES-0951576). Woolley acknowledges support from the Logistics Management Institute, and Glotter acknowledges support from an NSF Graduate Fellowship (no. DGE-1144082).

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.

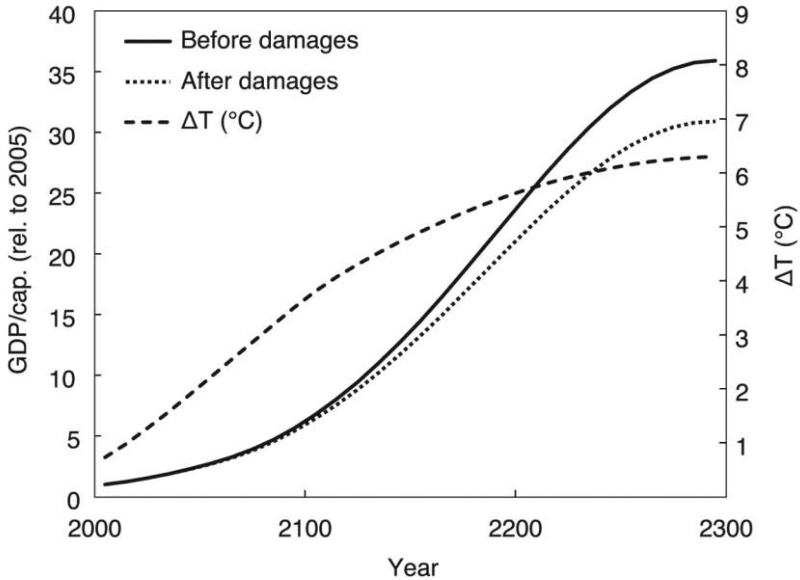

Figure 1. Evolution of per capita GDP from IWG-DICE (IMAGE scenario with climate sensitivity of 3°C/doubling). Future generations are much wealthier both with (*dotted line*) and without (*solid line*) climate change, despite temperature increase of over 6°C.

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

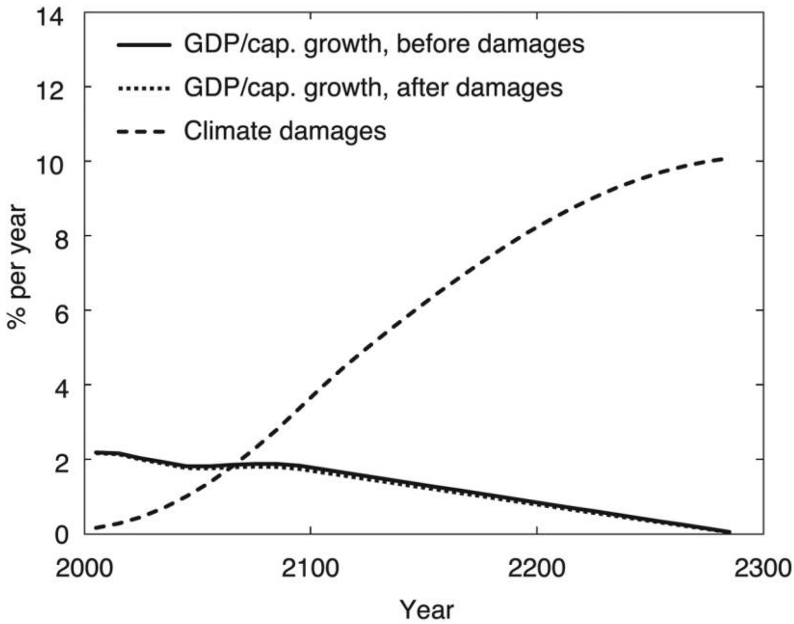

Figure 2. Evolution of GDP growth rate (percent/year) from IWG-DICE (IMAGE scenario with climate sensitivity of 3°C/doubling), and climate harms to output (also percent/year).

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 ($D_t Y_t$) were simply thrown away. The relative magnitude of climate harms D_t is represented by a quadratic

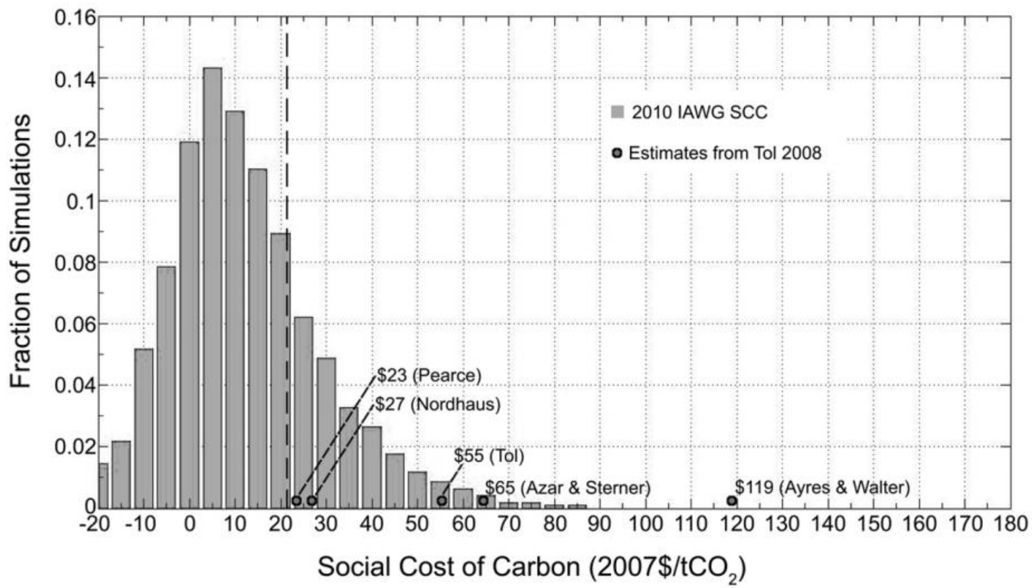

Figure 3. Distribution of 2010 IWG estimates of the year-2010 SCC from all three models for a 3 percent discount rate. Data were digitized from Figure A8 of IWG (2010). (Raw IWG SCC data are no longer available.) Dashed line is mean value across models, \$21/tCO_2. Mean (median) SCC values for DICE, 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

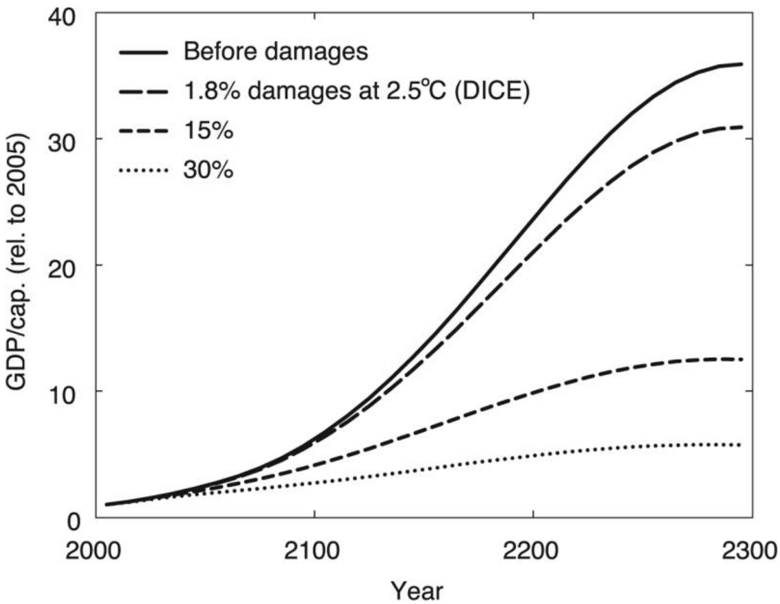

Figure 4. Per capita consumption levels as a multiple of per capita consumption in 2005, for IWG-DICE but with varying damage calibration points: as in the IWG model (1.8 percent of GDP for a 2.5° temperature increase), and at 15 percent and 30 percent of GDP for the same temperature increase.

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

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

(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:

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

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.

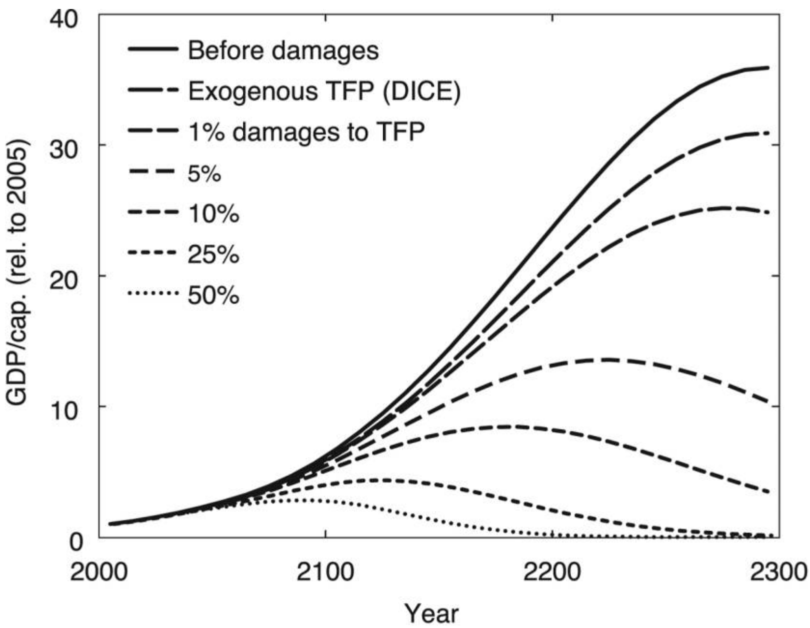

Figure 5. Per capita consumption levels as a multiple of per capita consumption in 2005, for IWG-DICE but with damages applied to TFP at specified levels. See online Appendix E for color version of figure.

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

Harms to TFP	DICE Model, with 3% Discounting		Standard DICE Model with Endogenous Discounting		
	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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