U Penn readers:

I am presenting two short, closely-related papers today. One has been submitted to the journal Climatic Change and is awaiting referee reports. My co-authors and I will have time to make revisions on what will likely be a revise and resubmit so comments now will be helpful. Climatic Change imposes tight page limits, so the language is terse and assumes some background knowledge. Additional details can be found in the appendices for those who want to read more. (They also require submission in their journal format with tiny font. Sorry.) My co-authors and I have just started the second paper but it is very closely related and has a number of possible legal implications so I thought it would be worth presenting some background on the question we address, our modeling strategy, and our preliminary results.

David Weisbach

Metrics for Short-Lived Greenhouse Gases

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Background on short-lived gases

Human activities lead to the emission of a number of greenhouse gases. Increased concentrations of greenhouse gases in the atmosphere are expected to raise the Earth's mean temperature and cause other detrimental changes to the climate.

The dominant greenhouse gas (by mass) produced by human activity is carbon dioxide (CO_2). Carbon dioxide is produced from the combustion of fossil fuels and from the decay of lumber after land is deforested. Of the nearly 40 billion tons of anthropogenic CO_2 currently emitted each year, roughly 1/3 will persist in the atmosphere for 10,000 years or more.

Human activities also produce relatively smaller (by mass) emissions of several gases that have more potent effects while they are in the atmosphere but also have a shorter lifetime. These short-lived gases include methane (CH_4), produced in rice cultivation or in the bellies of livestock such as cows and sheep, or emitted directly as leakage of unburnt natural gas; nitrous oxide (N_2O), produced by soils as a byproduct of fertilizer application; and various industrial gases such as hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride. Unlike CO_2, these gases disappear quickly after emission: the atmospheric half-life of methane is approximately a decade and that of N_2O around a century.

Any policy designed to reduce climate change must make a choice about the mix of gases to reduce. Different choices would have very different implications for costs and for who bears the costs, because the various greenhouse gases have different sources, abatement costs, and effects on the economy. Constructing an efficient climate mitigation policy requires determining the relative marginal harms of these different gases, and therefore determining the relative importance of warming that happens on short or long timescales.

Current policy instruments already implicitly or explicitly involve decisions on the relative importance of short-lived versus long-lived greenhouse gases. For example, the Kyoto Protocol commits signatories to specified reductions in emissions of six greenhouse gases compared to a baseline year (e.g., had the US ratified the treaty, its 2012 emissions would have to have been 93% of 1990 emissions). Kyoto could apply an implicit trade-off in setting separate targets for each gas. In practice Kyoto mandates an overall target and uses an explicitly defined exchange rate (described below) to allow countries to choose a portfolio of reductions in different gases.

Similarly, the debate over fracking in the United States depends on views of the tradeoffs between methane and carbon dioxide emissions. Fracking has increased the supply and lowered the cost of natural gas (methane), which means that natural gas is increasingly replacing coal for electricity production. Because natural gas has a lower carbon content per unit of energy, replacing coal by gas in power generation lowers emissions of CO_2. However, fracking also results in the direct leakage of unburnt methane during the extraction process. The relative weight we put on increased methane emissions versus decreased CO_2 emissions from coal substitution will in part determine whether fracking should be viewed as environmentally friendly or detrimental.

The weights we put on different gases may also have distributive effects, either within or between countries, since countries differ in their emissions of methane or nitrous oxide relative to carbon dioxide. For example, New Zealand's large sheep population and dairy industry mean the country has methane emissions nearly twice as large relative to CO_2 emissions as does the U.S. Whether New Zealand is a large emitter of greenhouse gases depends on how we view those emissions.

Global Warming Potential (GWP) and other metrics

The Kyoto Protocol, all other legal climate mechanisms (to our knowledge), and virtually every study weighting the relative importance of different greenhouse gases does so using a metric known as the "global warming potential", or GWP. The GWP of a gas is a function of what is known as radiative forcing. Radiative forcing is defined as the influence of a gas (or other factor such as an aerosol) in altering the balance of incoming and outgoing energy. It is roughly an index of how much temperature change a unit of gas is likely to create.

GWP is defined as the amount of radiative forcing from the emissions of a unit of a gas relative to the radiative forcing from the emissions of a unit of carbon dioxide. It tells us the relative potency of a gas. To account for the fact that gases do not persist in the atmosphere forever and that different gases have different lifetimes, the GWP uses a fixed time period, usually 100 years. It compares the increase in radiative forcing over 100 years from the emission of a unit of a gas today as compared to the forcing over 100 years from the emission of a unit of CO_2 today. It is the relative potency of a gas over 100 years.

In particular, if a_i is the instantaneous radiative forcing per unit of mass of a gas and $C_i(t)$ is the time-dependent mass of the gas left in the atmosphere if a unit is emitted at time 0, the product, $a_i C_i(t)$, is the forcing at any moment in time. We can add up this product over the specified time period for each gas to generate the total forcing over the time period. In mathematical notation, the GWP for a 100-year horizon for gas x is defined as

$$GWP = \frac{\int_0^{100} a_x \left[C_x(t) \right] dt}{\int_0^{100} a_{CO_2} \left[C_{CO_2}(t) \right] dt}.$$

Using this formula, the 100-year GWP of methane is 25 while the 100-year GWP of nitrous oxide is 2,980. The 100-year GWP of HFC-23 is 14,800 and the 100-year GWP of SF_6 is 22,800. That is, under the GWP measure, reducing one ton of emissions of SF_6 has the same benefit as reducing 22,800 tons of CO_2.

The implication of the GWP numbers is that we should be willing to spend much more to reduce emissions of methane, nitrous oxide and especially trace gases than to reduce an equivalent amount of CO_2. For example, the GWP of methane is 25. This implies that methane has 25 times more radiative forcing over 100 years than does carbon dioxide. If we were willing to spend $10 to stop the emission of a ton of CO_2, and if we use GWPs as our metric, we should be willing to spend $250 to stop the emission of a ton of methane.

The Kyoto Protocol and (to our knowledge) all other legal mechanisms relating to climate change use GWPs. The Kyoto Protocol covers six greenhouse gases and imposes a unified target for reducing emissions of these gases (for each country). It uses GWPs to translate emissions of non-CO_2 gases to the equivalent reduction in carbon dioxide to determine if the target is met. While the EU Emissions Trading System does not directly cover methane, it allows credits or offsets for reductions of methane or other gases in developing countries. It uses GWPs to convert the reductions into carbon equivalents.

GWPs are also used in policy studies. For example, GWPs are used in widely circulated estimates of the importance of various greenhouse gases. As an illustration, the chart included in the Appendix was generated by the World Resources Institute. It maps the sector, the end use activity and the gas for the major greenhouse gases. It indicates at the bottom that the estimates are in what are called CO_2 equivalents or CO_2-e's. These are simply the mass of a gas multiplied by its GWP. Thus, the weighting in sources such as this rely on the validity of GWPs. The IPCC also uses GWP's in its measures of emissions.

GWPs have been widely criticized. There is some uncertainty about the GWP estimates because, for example, there is uncertainty about the atmospheric lifetime of CO_2. The IPCC has to regularly update GWPs as a result of new scientific studies. Treaties and other legal instruments typically have to lock in GWPs from an earlier date to prevent constant changes in targets.

GWPs also have an implausible discount function. They add up radiative forcing over a specified time period but do not count any forcings beyond that time period. It is as if the discount rate were zero for 100 years and then immediately jumped to infinity. This means that the GWP calculation treats effects in, say, 75 years the same as effects in 5 years while treating effects in 101 years as not existing at all. (Note that the original formulation of GWPs for greenhouse gases did include discounting. We are not sure yet why and when this got dropped.)

Most important, GWPs may not be measuring what we care about. We care about emissions of greenhouse gases because those emissions will hurt people or other living things. Radiative forcing is connected to how much emissions will hurt people but the relationship is not simple. Consider the following chain of causation:

Concentration changes → forcing → climate impacts (temps) → economic impacts → damages

GWPs measure effects of forcing, which is well up in the chain of causation. For a given level of forcing (at a given time period), we may see very different economic impact and very different levels of damages. For example, damages from climate change likely go up faster as temperatures increase: the damages from increasing temperatures relative to preindustrial levels by 1°C are likely small (we have just about increased them by this much already) while the damages from increasing temperatures by 6° or 7° may be catastrophic. If damages are nonlinear in temperature increases, we cannot use forcings as a measure of how much we care about the effects of emissions.

Because of the problems with GWPs, numerous authors have proposed alternatives. The alternatives vary in where in the chain of causation they measure the effects, how they deal with differing atmospheric effects, and whether they measure the effects of a pulse of emissions (like GWP does) or whether they use a stream of emissions determined by assuming some sort of emissions scenario.

The obvious measure would be to relate a concentration change in a gas to the harm caused, as measured in present value terms. We explore such a measure in our study. The problem we address is the enormous uncertainty in performing such a calculation. We focus on uncertainty regarding damages but there is uncertainty at each point in the chain of causation. The further up the chain of causation used for a given metric, the less the uncertainty but the lower the correlation between the metric and the outcome of interest.

Most of the suggested metrics use an earlier stage in the chain of causation. For example, Manne and Richels (2001) look at the trade-off of gases in reaching a prescribed temperature target. They choose a temperature limit such as limiting increases to 2° and then use a computational model to calculate the optimal mix of reductions in various greenhouses gases to stay within that target in a specified time period, such as 200 years. Given this mix, they calculate the tax on each gas that would induce the needed reductions (i.e., the shadow price of the gas). The ratio of these prices tells the relative weightings for each gas in a given year. We can think of the Manne and Richels measure as a cost effectiveness measure. It makes an assumption about economic impacts that implies a 2° or 3° target, so they do not model damages. They do, however, have to measure the costs of emissions reductions so that they can calculate the optimal mix, and there is great uncertainty in these estimates. Johansson (2012) proposes a similar estimate. These measures also are opaque because they rely on a computational model to determine the mix of gases and the shadow price. Different modeling choices or even numerical solution algorithms can lead to different values.

Scientists have tended to want to keep the measure closer to the physical part of the chain of causation because they feel reasonably comfortable making these estimates and not making the necessary economic or valuation estimates. For example, Shine et al (2005, 2007) propose a measure they call the Global Temperature change Potential or GTP. This is the temperature change at the end of a time horizon from a pulse of emissions at the beginning, relative to that of CO_2. It moves one step further down the chain of causation than the GWP and because it involves a single output – temperature at a specified time period – avoids having to integrate over time. Mean global temperature change, proposed by Gillett and Matthews (2010) is a hybrid of GWPs and GTPs: it measures the integrated temperature change over time from a pulse of emissions.

The problem with purely physical-based measures is that they do not measure what we care about. If climate change did not affect people (or other living things), we would not care about it. We do not care about the temperature on Jupiter. Climate change only matters to the extent that it has effects, so a measure that ignores those effects would only be correct by sheer happenstance.

Our Study

We consider a set of measures called the social cost or marginal cost measures. The social cost of a gas is the present discounted value of the change in consumption due to the emissions of an additional unit of the gas. It is the marginal cost (measured in the value of lost consumption) of emissions.

The social cost of carbon, or the SCC, is required to be used by federal agencies in cost-benefit analysis. If, for example, a regulation reduces emissions by an estimated amount, the dollar benefit of the reduction is the SCC multiplied by the amount of the reduction. OMB, along with a group of affected agencies, calculated a unified SCC for use in all significant regulatory actions. They estimated it using three different computational models each run over a number of scenarios and climate sensitivities. The SCC was officially set at \$21/tCO_2. It has recently been updated and is now \$33.

Because they apply at the end of the chain of causation, social cost measures measure what we care about but this also means that they are subject to great uncertainty. They may vary greatly depending on explicit or implicit modeling assumptions. In the other paper for today's workshop, we examine the sensitivity of the SCC estimate done by OMB to assumptions about how climate change effects the economy. The implicit assumption, which arises because of a modeling artifact, is that climate change basically does not affect the economy. Even when temperature increases are extreme – at levels where evidence from prior periods in the Earth's history indicate dramatically different conditions – the economy continues to grow and people living in the future are many times wealthier than people are today. If climate change makes people poor (or not as many times wealthier as they would otherwise be), say because it affects growth rates or destroys the economy, the estimates of the SCC can go up by many orders of magnitude. Our conclusion in our other paper is that the SCC is highly sensitive to modeling assumptions about the effect of climate change on growth rates, suggesting that this effect is critical to understand.

(Note that in a separate project, one of us has developed a website which allows users to run one of the models used for the SCC estimates via a simple web-based interface. Among other things, you can examine the how the parameter choices, particularly how assumptions about climate change and growth rates affect the social cost of carbon by manipulating the sliders. This can be found at http://webdice.rdcep.org. Comments on this website would be most welcome. The public launch is imminent.)

In this study, we consider the social cost of methane (SCM). The SCM is an absolute dollar number, the present discounted value of the loss in consumption due to the emission of an additional ton of methane. The GWP is a relative number: it is the forcings over a specified time period of a gas relative to the forcings over that same time period for carbon dioxide. To compare the social cost measure to the GWP measure, we take the ratio of the SCM to the social cost of carbon. For example, if the social cost of carbon is $20 and the social cost of methane is $400, these numbers tell us that methane is 20 times more important to reduce (per ton) than carbon dioxide, which is the same type of information that GWP purports to provide. If these were the numbers from a study, they would tell us that methane is slightly less important to reduce than the GWPs numbers imply because the GWP of methane is 25. The GWP numbers tell us that methane is 25 times more important than carbon dioxide and the social cost numbers would be telling us that it is 20 times more important.

There are, to our knowledge, three published estimates of the social cost of methane, coincidently one for each of the models used by OMB in its estimate of the SCC. Hope (2006), Waldhoff, Anthoff, Rose and Tol (2011), and Marten and Newbold (2012). They all produce estimates of the ratio of the SCM to the SCC that are roughly on par with the 100-year GWP of methane. Marten and Newbold use the same model calibration for the DICE model that the OMB used for its SCC calculation, modified to include methane. They calculate that the ratio of SCM to SCC is higher than the GWP for methane, which means that we should focus more attention on methane than we would if we used GWPs. Hope calculates a ratio of 21, which is modestly lower than the GWP value of 25.

Pierrehumbert (forthcoming) has suggested that these calculations must be wrong. His argument is that the effects of emissions of methane (and to a lesser extent nitrous oxide) are short-lived because its atmospheric life is short. Reductions in methane, therefore, do not prevent continued temperature increases if we continue to emit carbon dioxide. If we care about long-term stabilization of temperatures, CO_2 and not short-lived gases should be our primary focus. Labeling short-lived gases short-lived climate pollution or SLCP, he argues:

> SLCP mitigation measures have little or no value unless CO_2 emissions are already on a trajectory to go to essentially zero, and [] there is little or no harm done by delaying SLCP mitigation until such measures are in place, whereas any significant delay in mitigation of CO_2 causes great harm.

Our paper will explore the difference in these views. If the estimates of the SCM are indeed too low, what modeling assumptions drive the low estimate and are those assumptions reasonable?

To study these questions, we use the same model we used to examine sensitivity of the SCC to assumptions about harms from climate change. The basic idea is that if climate change leads to serious and long-term harms to the economy, stabilization of temperatures over the long term becomes more important. The relative importance of CO_2 will likely be higher in this case because the emission of a ton of CO_2 continues to harm the economy over a long time period whereas an emission of a unit of CH_4 does not. If the harms are serious, the effects of CO_2 are magnified.

A second, more technical effect is that if the economy is harmed significantly, the implicit discount rate is lower. A lower discount rate means that harms in the future are valued more, resulting in harms from CO_2 being valued more because they take place further in the future than harms from CH_4. That is, we explore whether the implicit assumption of no serious harms from climate change in the prior estimates of the SCM lead to a significant overestimate of its value.

The policy payoffs could be significant. As noted, the debate over fracking depends on how one measures the effects of methane emissions. In addition, emissions trading systems impose explicit trade-offs for methane and CO_2, prices which may be significantly wrong. Incorrect pricing leads to mitigation efforts in the wrong parts of the economy.

We have just begun this effort and only have the most preliminary model runs available. There are a number of technical issues in the modeling driven in large part by the vastly different time scales for methane and CO_2. The model we use, the DICE model, is a simple model, designed to run quickly, but this means that it is not robust to changes, creating some technical headaches in adding methane. Methane also interacts with nitrous oxide, so modeling the forcing effects of methane requires assumptions about nitrous oxide. Also, because the prior model did not explicitly include methane, we have to construct a baseline path for methane (and nitrous oxide) that is consistent with the implicit assumptions in the model.

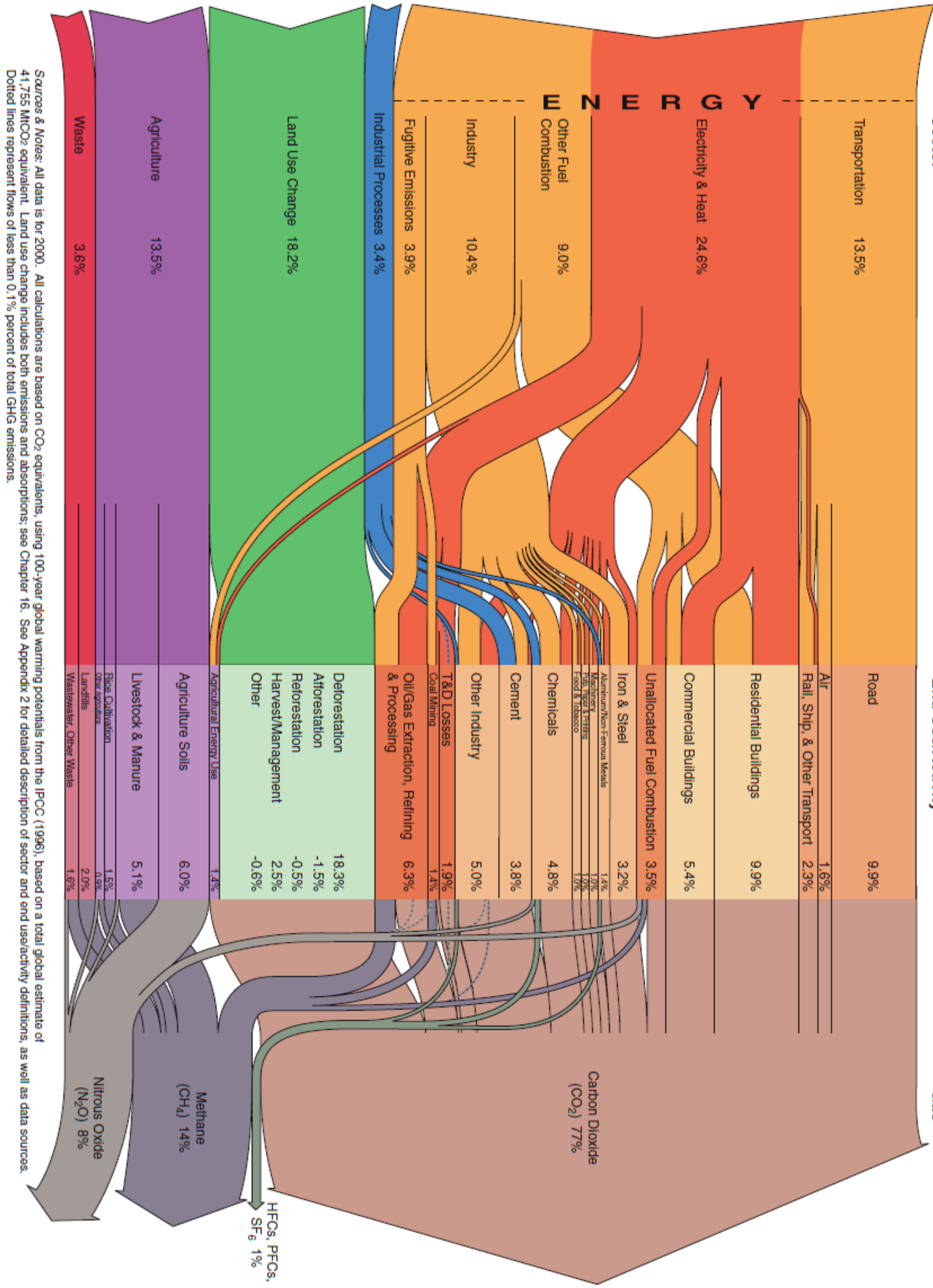
The tables below show the results from our preliminary runs. The last table shows the ratio of the SCM to the SCC which can be compared to the GWP. As can be seen, the ratio is uniformly less than 25 (the GWP of methane) and under many specifications it is much lower. As damages from climate change get worse, the ratio goes down. To the extent policy is set by a concern for the worst cases, methane becomes less important and in sufficiently bad cases, it does not matter at all. (The negative SCM values appear to be a modeling artifact, but we are still sorting this out.) The ratio is also highly dependent on the discount rate, which makes sense because the discount rate determines how we weigh differing time periods and the key difference between methane and CO_2 is the effects in different periods.

SCC	Fixed discounting	Variable discounting, η=2 ρ=1%	Variable discounting, η =1 ρ=0.1%
DICE damages	50	15	185
5% damages to TFP level	143	52	1,151
10% damages to TFP level	200	119	1,990
25% damages to TFP level	290	1,126	4,202

SCM	Fixed discounting	Variable discounting, η=2 ρ =1%	Variable discounting, η =1 ρ=0.1%
DICE damages	504	243	862
5% damages to TFP level	1,852	733	6,846
10% damages to TFP level	2,839	1,284	10,242
25% damages to TFP level	4,898	12	10,661

SCM/SCC	Fixed discounting	Variable discounting, η=2 ρ =1%	Variable discounting, η =1 ρ=0.1%
DICE damages	10	16	5
5% damages to TFP level	13	14	6
10% damages to TFP level	14	11	5
25% damages to TFP level	17	0	3

Appendix: Typical emissions chart dependent in GWPs:



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

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Abstract One of the central ways that the costs of global warming are incorporated into U.S. law is in cost-benefit analysis of federal regulations. In 2010, to standardize analyses, an Interagency Working Group (IAWG) established a central estimate of the social cost of carbon (SCC) of \$21/tCO_2 drawn from three commonly-used models of climate change and the global economy. These models produced a relatively narrow distribution of SCC values, consistent with previous studies. We use one of the IAWG models, DICE, to explore which assumptions produce this apparent robustness. SCC values are constrained by a shared feature of model behavior: though climate damages become large as a fraction of economic output, they do not significantly alter economic trajectories. This persistent growth is inconsistent with the widely held belief that climate change may have strongly detrimental effects to human society. The discrepancy suggests that the models may not capture the full range of possible consequences of climate change. We examine one possibility untested by any previous study, that climate change may directly affect productivity, and find that even a modest impact of this type increases SCC estimates by many orders of magnitude. Our results imply that the SCC is far more uncertain than shown in previous modeling exercises and highly sensitive to assumptions. Understanding the societal impact of climate change requires understanding not only the magnitude of losses at any given time but also how those losses may affect future economic growth.

Keywords SCC · climate change · IAM · climate impacts · DICE · growth

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1 Introduction

One of the central ways that the costs of global warming are incorporated into U.S. law is through the use of the social cost of carbon (SCC) – the present-value cost of an additional ton of CO_2 emissions – in cost-benefit analysis. Federal agencies are required by executive order to assess the costs and the benefits of each significant regulation. In 2009, in an effort to standardize analyses, the Office of Management and Budget (OMB) convened representatives from 12 agencies to participate in an Interagency Working Group on the social cost of carbon (IAWG). The IAWG based their study on three simple, commonly-used integrated assessment models (IAMs) that represent the effects of climate change on the global economy – DICE (Nordhaus, 2008), FUND (Anthoff et al, 2009), and PAGE (Hope, 2006) – and so provides a useful framework for examining issues in modeling the cost of climate change. The models were tuned to match the same socioeconomic scenarios and climate sensitivities, and were used to predict economic trajectories in the baseline case and with one additional ton of CO_2. The SCC is computed as the present value difference in consumption between the two cases. The IAWG's central SCC estimate (IAWG, 2010) must be used in cost-benefit analysis of any regulation that affects carbon dioxide emissions.

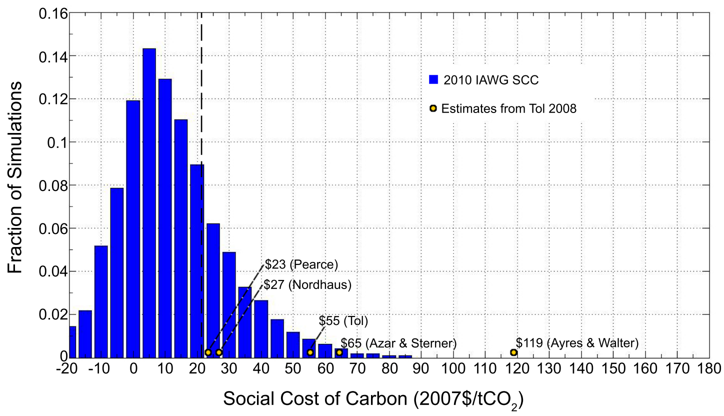

Fig. 1: Distribution of 2010 IAWG SCC estimates from all three models, for a 3% discount rate. Data were digitized from Figure A8 of IAWG (2010). (Raw SCC data are no longer available.) Dashed line is mean value across models, \$21/tCO_2. Mean (median) SCC values for DICE, PAGE, and FUND are \$28 (\$25), \$30 (\$12), and \$6 (\$0.5) /tCO_2, respectively (IAWG (2010) Tables A3 and A5). Negative SCC values imply that climate change is net beneficial to society; all are confined to FUND, which assumes gains in the agricultural sector under moderate warming (Greenstone et al, 2013). Dots show all SCC estimates from the Tol (2008) review with 3% discount rate, as average values from each study.

The IAWG's distribution of SCC values is relatively narrow and consistent with previous estimates. The distribution with an OMB-required fixed 3% discount rate is right-skewed with a median of ∼ \$12/tCO_2, a mean of \$21/tCO_2, and a 95th percentile value of \$68/tCO_2 (Fig. 1). A 2008 meta-analysis of SCC estimates showed a similar right-skewed distribution, with values from peer-reviewed studies using a 3% discount rate ranging from \$23-119/tCO_2 (Tol, 2008). Several studies since 2010 have revisited the IAWG estimates and generally suggested modest increases (e.g. Johnson and Hope, 2012; Kopp et al, 2012). In 2013, the IAWG used updated model versions to provide a revised SCC distribution about 50% higher (IAWG (2013), and see Online Resources for details). Even inclusive of these later studies, the range of SCC values is narrow enough to appear inconsistent with the widely held view that the societal consequences of climate change over hundreds of years are highly uncertain.

The IAWG models share one notable feature: although climate damages can become large as a fraction of output, they do not significantly alter economic trajectories. As an example, we present model output generated with a single IAM, scenario, and climate sensitivity (the DICE model, IMAGE scenario, and 3°C/CO_2 doubling, all discussed further in Section 2). The IMAGE scenario posits that without climate change, the global economy would grow at an average annual rate of 1.3% (1.2% per capita), yielding per capita income 35 times larger by 2300 (Fig. 2).[1] This strong growth continues even under basecase CO_2 emissions and climate change. Although global mean temperature rises over 6°C by 2300, accumulation of wealth is only slightly reduced: per capita income rises by a factor of 30 rather than 35. The persistence of growth in the face of climate change in DICE and similar models has been noted by other authors, in particular Weitzman (2011).

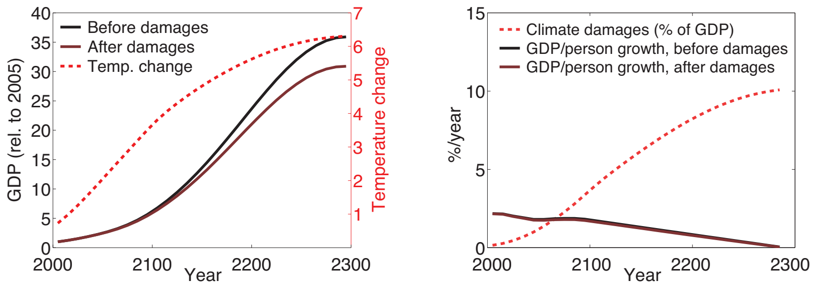

Fig. 2: Evolution of per capita GDP (left) and per capita annual GDP growth (right) from IAWG DICE-IMAGE, without (black) and with (brown) climate change damages. Left panel includes projected global mean temperature change (red). Right panel includes annual GDP losses due to climate damages (red).

[1] In the economic scenarios used by the IAWG, average annual growth rates to 2300 range from 1-1.3% (0.8-1.3% per capita), producing gains in per capita income of 4-6 times by 2100 and 12-40 times by 2300.

Persistent growth leads to SCC values likely too low to justify significant action to mitigate climate change. Spending to benefit much wealthier future generations would need an extraordinary high return to be warranted. In the IMAGE example, with 30x growth by 2300 despite climate change, recommending immediate mitigation spending would be analogous to asking the average current United States household, with an annual family income of \$50,000, to transfer wealth to a family with an income of \$1.5 million. Comparison to mitigation costs is also informative. The central SCC estimate of \$21/tCO_2 would not likely yield significant transformation of the electric sector, even if it were taken as a recommended carbon tax, since the 2010 minimum U.S. "price premium" for renewable electricity generation is ∼\$22/tCO_2 (Johnson and Moyer, 2012).[2] (See Section 5 for discussion of optimal taxes). The IAWG process appears to produce a policy recommendation that would not significantly drive technological evolution for emissions reductions.

Continued economic growth in the face of climate change is inconsistent with many (admittedly qualitative) statements by experts that climate change may have strongly detrimental effects to human society. This discrepancy suggests that the models used in the IAWG process may not capture the full range of possible consequences of climate change, i.e. that some aspect of parameter space remains unsampled. In this study, we explore which aspects of the IAWG process produce the apparent robustness in SCC estimates. In particular, we examine one possibility unexplored by any study, that climate change may directly affect the productivity of the economy.[3]

2 DICE and the Interagency SCC Estimation

We focus on one of the three models used in the IAWG process, DICE (Dynamic Integrated Climate-Economy). DICE is an open-source IAM with a long history of use in studies of the costs of global warming (Nordhaus, 1993, 1994, 2007, 2008). Our analysis uses the model version modified by the IAWG ("interagency DICE"), which was based on the 2007 release ("standard DICE"). We examine only DICE because, of the three IAWG models, it is the only general equilibrium model and therefore the only one capable of capturing the potential growth impact of climate change that is the focus of this study. (FUND and PAGE are both partial equilibrium models in which economic growth is exogenously specified.) DICE is also open source, widely-known, and based on standard economic theory. For simplicity, we consider only a single representative socioeconomic trajectory (from IMAGE) and climate sensitivity (3°C/CO_2 doubling, the median value in the distribution used in the IAWG study), but the underlying arguments apply generally.

[2] \$22/tCO_2 is the premium commercial windpower in high-wind onshore sites. Commercial dam-based hydropower is lower-cost.

[3] Fankhauser and Tol (2005) 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 the labor and capital devoted to R&D. Climate change reduces usable output as in DICE, in turn reducing savings and the capital available to the R&D sector, slowing growth.

DICE is based on the Solow-Swan growth model (Solow, 1956; Swan, 1956). It treats the entire world as a single region, with output generated by labor and capital combined at a prescribed rate of productivity. Economic output is represented by a standard Cobb-Douglas production function:

$$Y_t = A_t \cdot N_t^{1-\alpha} K_t^{\alpha} \tag{1}$$

where Y_t is total output, K_t is capital, N_t is labor, and A_t is Total Factor Productivity, "TFP". TFP is intended to capture all changes to output that cannot be explained by changes in labor or capital, and is often envisioned as varying because of technological change. The parameter α (the elasticity of output with respect to capital) is set in DICE to 0.3, reflecting broadly accepted estimates for the share of income going to capital (Acemoglu, 2008). Output per capita, Y/N, is then a function only of productivity and capital stock per capita:

$$\frac{Y_t}{N_t} = A_t \cdot (K_t/N_t)^{\alpha}. \tag{2}$$

Capital grows through savings and depreciates at an annual rate δ, i.e. capital in one time period is equal to depreciated capital in the previous period plus savings:

$$K_{t+1} = K_t(1-\delta) + sY_t. \tag{3}$$

The savings rate s is fixed at 22% and δ at 10%.

CO_2 emissions follow a fixed path in interagency DICE, in contrast to standard DICE in which emissions *intensity* (CO_2 per economic activity) is exogenous. Emissions are translated to atmospheric CO_2 concentration through a simple 3-box model of the ocean and atmosphere and a linearized representation of ocean CO_2 uptake. (See Online Resources for longer discussion of the DICE carbon cycle). Temperature evolution is determined by the specified climate sensitivity and a simple representation of heat transfer in the ocean.

The climate-economy feedback loop is closed by allowing temperature change to affect the economy. Damages from climate change are modeled as a fractional loss D of annual economic output that is a function of global mean temperature. Equation 1 becomes:

$$Y_t = (1-D_t) \cdot A_t \cdot N_t^{1-\alpha} K_t^{\alpha}. \tag{4}$$

The fractional loss of output D due to climate damages ranges from 0 (no loss) to 1 (loss of all output):

$$D_t = 1 - \frac{1}{1 + a_2 \Delta T_t^2}. \tag{5}$$

where ΔT_t is the global mean temperature change at time t. The damage parameter a_2 is set based on two assumptions: no change in output at 0° C temperature change and a 1.8% loss of GDP at a "calibration point" of $\Delta T = 2.5$°C, yielding $a_2 = .0028388$ (Nordhaus, 2007, 2008). The loss estimate of 1.8% is drawn from a meta-analysis of published climate impacts studies (Nordhaus, 2007, 2008; Nordhaus and Boyer, 2000).

Because the IAWG protocol required that the three IAMs be run with common scenarios, the IAWG modified DICE, fixing parameters that would ordinarily vary and tuning the model to match specified scenarios of economic output and emissions (2000-2100 forecasts presented at the 2009 Stanford Energy Modeling Forum Exercise 22; see Clarke and Weyant (2009)). Tuning involved constructing exogenous productivity (TFP) curves to reproduce the prescribed economic evolution. To extend scenarios an additional two hundred years to 2300, the IAWG assumed that population and GDP growth rates decline linearly from 2100 forward, reaching zero in 2200 and 2300, respectively. The resulting assumptions for the IMAGE scenario are shown in Figure 3.

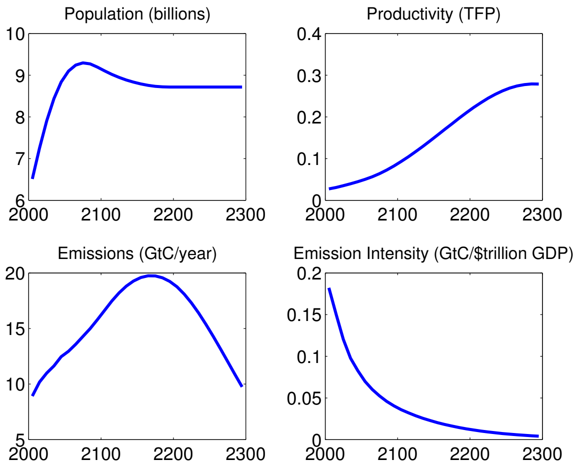

Fig. 3: Three exogenous parameters – population, TFP, and annual CO_2 emissions – and implied carbon emission intensity for the IMAGE scenario. Productivity increases by a factor of 10 between 2000-2300, and emissions intensity falls by a factor of 44. Cumulative emissions during this timeframe are $\sim$ 4,600 GtC.

To generate pathways of SCC values over time, each model was run with a base-case emissions scenario and sequentially with an additional ton of CO_2 emissions in each scenario year. The SCC in year τ is the net present value of the difference between consumption (output less savings) C_b in the base case and C_1 in the case with additional emissions in year τ:

$$SCC_\tau = \sum_{t=\tau}^{T} \frac{(C_b - C_1)_t}{(1+r)^t} \tag{6}$$

where r is the discount rate. Because climate damages are assumed nonlinear with global mean temperature, the SCC rises over time, approximately doubling between 2000 and 2050: damages from an additional ton of CO_2 are larger when previous warming is larger. The IAWG used a fixed discount rate of 3%, required by OMB guidelines, but also reported results for discount rates of 2.5% and 5%. The 2010 SCC value derived in our single-scenario, single-climate-sensitivity analysis is similar to the value obtained by the IAWG with DICE using a distribution over scenarios and parameters: \$34/tCO_2 vs. \$28/tCO2 in IAWG (2010).[4]

3 Robustness of growth in DICE and alternative specifications of climate damages

In interagency DICE, economic growth continues despite substantial climate damages because past damages minimally affect economic trajectories. As shown in Figure 2, economic growth remains positive in the year 2300 even when global mean temperature rise exceeds 6 °C and the annual loss of output is over 10% of GDP. Societal income at this point would have been 35x present without climate change and is 30x present with it, but the bulk of that difference is the 10% annual climate-related loss of output, which alone would lower income to 31.5x present. The cumulative effects of two previous centuries of changed climate make a negligible contribution.

Annual climate losses in DICE are comparable to historical major economic shocks, but the lack of cumulative effects may not be realistic. The Tohoku earthquake in March 2011 is estimated to have cost Japan 3.3%-5.2% of GDP in reconstruction costs (OECD, 2011), and economic contraction in the U.S. during the Great Depression was 8.6%, 6.5% and 13.1% in the years 1929-30, 1930-31 and 1931-32, respectively (BEA, 2011). During the Great Depression, economic contractions were progressive, with each year's loss evaluated against that of the previous year, so that by 1931-32, output was more than 25% lower than in 1928-29. In DICE, by contrast, climate damages in a given year propagate only weakly into the future.

Weak propagation of climate damages in DICE occurs because damages are applied only to output, and can affect growth only indirectly, through two pathways. First, the growth rate dY/dt includes a small term $(dD/(1-D))/dt$ related to year-over-year fractional changes in the damages themselves, which increase as warming progresses. Second, climate damages lower savings, because savings are a fixed percentage of output. Harm from climate change reduces capital available in future years, lowering output in those years. Neither effect is large, however.

We test the robustness of growth in DICE by increasing the magnitude of climate damages to highly unlikely values, setting losses at the 2.5 °C calibration point to 15% and 30% of GDP rather than the default 1.8% (Fig. 4a-b). The most extreme value used is over six times the maximum of the IPCC's estimated plausible range of damages (Pachauri, 2007) and yields annual climate-related losses of over 70% of GDP by 2300. Even these catastrophic losses do not cause economic contraction. The assumed exogenous factors driving growth in DICE outweigh any plausible effects of climate change.

The robustness of growth in DICE suggests that the specification of climate damages may not reflect the full range of possible harms. The model has only four pa-

[4] Interagency DICE uses 10-year timesteps beginning with 2005, so our stated 2010 SCC value is the average of 2005 and 2015. The IAWG "central" value of \$21/tCO2 averages estimates from all models.

rameters that can be affected by climate change: output Y, capital K, labor N, and productivity A. In DICE, damages affect only output. Several previous authors have tested alternative representations of climate damages, including applying them to capital (e.g. Ackerman et al, 2010; Kopp et al, 2012), but all yield economies that grow in the face of large climate damages. We consider the possibility that climate change may reduce productivity growth. While the literature on climate change and technology includes many studies that consider how endogenously represented technological changes may affect climate (e.g. by promoting the development of low-emission energy sources; for examples see Acemoglu et al, 2012; Gillingham et al, 2008; Popp, 2004), no studies have considered the inverse problem, how climate change may directly affect productivity.

Research suggests that TFP levels can be partially explained by human capital accumulation, by the quality of government services, and by investment in R&D, all of which may be affected by climate change. (See reviews in Acemoglu, 2008; Barro and Sala-i-Martin, 2003). Some authors have argued that permanent losses of ecosystems and the use of capital and labor on adaptation instead of R&D may directly reduce growth rates (e.g. Pindyck, 2011, 2012). In a world where climate change causes losses to output, people may also reduce investments in areas that would have led to greater future output (e.g. education, health care, or public goods), yielding future productivity lower than in a world with no climate change. This indirect effect is analogous to the compounding impact of output losses to the capital stock. (See also Fankhauser and Tol, 2005). DICE cannot capture this effect because it does not allow savings to affect TFP, which is entirely exogenous.

The empirical evidence on the impact of climate change on productivity is limited but suggestive. Although temporary weather shocks are not exactly analogous to long-term climate changes, they can inform modeling of climate-related damages. Dell et al (2012) find that temperature shocks lead to several years of lower economic growth in low-income countries, affecting agricultural yields, industrial output, and political institutions, and reducing growth rates temporarily by $\sim$1.3 percentage points per $^\circ$C temperature rise. Bansal and Ochoa (2011) find that national temperature shocks reduce growth by 0.9 percentage points per $^\circ$C. Jones and Olken (2010) concur in finding reduced growth in agricultural and light manufacturing exports from poor countries after temperature increases. Of course, for longer-term climate changes, adaptation should result in smaller adverse impacts than those observed after short-term weather events. Still, Dell et al (2009) suggest that only half of the negative short-term impacts of temperature shocks are offset in the long run through adaptation.

In this work, we do not try to estimate how damages from climate change will affect TFP, if at all. Instead, we explore the sensitivity of the SCC estimate to the implicit assumption in DICE that damages do *not* affect TFP. To demonstrate the possible size of the effects, we examine the consequences of two formulations. First, we consider a damage function that imposes a fraction of annual damages on productivity (and the rest on output) but keeps the year-on-year damages for any given change in temperature the same as in the DICE formulation. Climate damages therefore reduce the level of TFP in any given year. Second, we consider a damage function motivated by a well-known endogenous growth model in which TFP growth is determined by the allocation of labor to inventing or manufacturing (Romer, 1990). Climate damages therefore reduce the *growth rate* of TFP. In both cases, climate effects on growth are negative. We do not consider the possibilities suggested by some authors, that investment in R&D could drive growth that counteract climate damages (Miao and Popp, 2013) or that natural disasters stimulate innovations and actually produce net growth (Skidmore and Toya, 2002). We explore only that part of the uncertainty in SCC values associated with the plausible possibility that climate change may negatively impact TFP.

3.1 Damages to TFP levels

In our first formulation, we allow a fraction of damages to reduce productivity rather than output. We solve for the implicit growth rate of TFP (g_{At}) in the exogenously specified path A_t according to

$$A_{t+1} = (1 + g_{At}) \cdot A_t. \tag{7}$$

We then allow a fraction f of damages to reduce TFP instead of decreasing output. That is, we specify a new path of TFP, A_t^*, that is reduced by climate damages:

$$A_{t+1}^* = (1 - f \cdot D_t)(1 + g_{At}) \cdot A_t^* \tag{8}$$

where $A_0^* = A_0$. The remainder of damages fall on output. Setting $D_{t_Y} = 1 - \frac{(1-D_t)}{(1-f \cdot D_t)}$, output equals

$$Y_t = (1 - D_{t_Y}) \cdot A_t^* \cdot N_t^{1-\alpha} K_t^{\alpha}.$$

This modification yields the same single-period fractional loss in consumption $(1 - D_t)$ as in the original specification. The trajectory of economic output is however highly sensitive to assumptions. Applying even a small fraction f of damages to TFP eventually produces negative growth rates, and applying 25% of damages to TFP causes economic collapse within the analysis timeframe (Fig. 4b-c).

3.2 Damages to TFP growth rates

As a second possibility, we consider a formulation of damages motivated by Romer (1990). That model contains two sectors, an inventing sector and a manufacturing sector; output of the former increases productivity of the latter. We allow damages to apply to both sectors equally. Damages then affect the economy in two ways: they reduce output of the manufacturing sector the same way they do in DICE – Equation 4 still holds – and they reduce output from the inventing sector, which reduces the growth rate of TFP according to

$$A_{t+1}^* = (1 + g_{At}(1 - D_t)) \cdot A_t^*. \tag{9}$$

This damage function is almost the same as that used by Pindyck (2011, 2012). (See Online Resources for derivation.) With this formulation, the DICE climate damages significantly reduce economic growth (Fig. 4b-c, dashed line). During the 300-year time period of our analysis, the effect is roughly similar to applying $f = 5\%$ of damages to TFP in Equation 8. Note that with the formulation of Equation 9, as opposed to that of Equation 8, *growth* in TFP can vanish but the TFP level cannot shrink, meaning climate change cannot produce a severe economic contraction. Equation 9 may therefore not capture all potential behavior of the climate and economic system. Nevertheless, it is informative that climate impacts on TFP can be a natural consequence of standard economic models.

3.3 Model adjustments required if climate change reduces growth

The assumption that climate change does not reduce growth is so ingrained in interagency DICE that the model contains three features that become unrealistic if growth is significantly reduced by climate damages. First, a fixed emissions pathway means that if the economy declines, emissions intensity (CO_2/GDP) can increase to implausible values. Second, a fixed discount rate is inconsistent with theories of the proper discount rate, which should be sensitive to economic growth. Finally, the DICE carbon cycle model is valid only on short (decadal) timescales and removes atmospheric CO_2 too quickly thereafter. If the discount rate is low because of low growth rates, longer timescales matter. The first of these features would tend to increase SCC values; the second two to decrease them. We therefore adjust the model to correct these unrealistic assumptions and recalculate economic trajectories (Fig. 4e-f, which repeat the cases shown in Fig. 4c-d). (For detailed discussion, see Online Resources.) Economic evolution remains broadly similar in the modified model, since reduced CO_2 emissions under economic decline are offset by slower ocean uptake of CO_2. Different damage formulations still produce a wide range of economic outcomes.

4 Comparison of SCC estimates

The varying economic outcomes with different treatments of climate damages produce SCC values that span many orders of magnitude (Table 1 and Fig. 5). Because the SCC is also sensitive to the choice of discount rate, a controversial issue, we show SCC calculated with two choices of discount rate parameters: values consistent with the discussion in IAWG (2010), and values used in Stern report (Stern, 2007) (Parameters are $\eta = 2$, $\rho = 1.5\%/yr$ and $\eta = 1$, $\rho = 0.1\%/yr$, respectively, in the Ramsey equation $r_t = \eta \cdot g_t + \rho$, where g_t is the growth rate. See Online Resources Sect. 5 for discussion.) For either discounting case, the resulting range of SCC values is much larger than in previous studies (e.g. Johnson and Hope, 2012; Kopp et al, 2012; Tol, 2008). As we have retained the same functional form for the magnitude of climate damages, this range reflects only uncertainty about how damages affect growth. Other authors have discussed alternate functional forms for damages (e.g. Ackerman et al, 2010; Kopp et al, 2012; Weitzman, 2009, 2011). Including those changes would increase the range of SCC values still further.

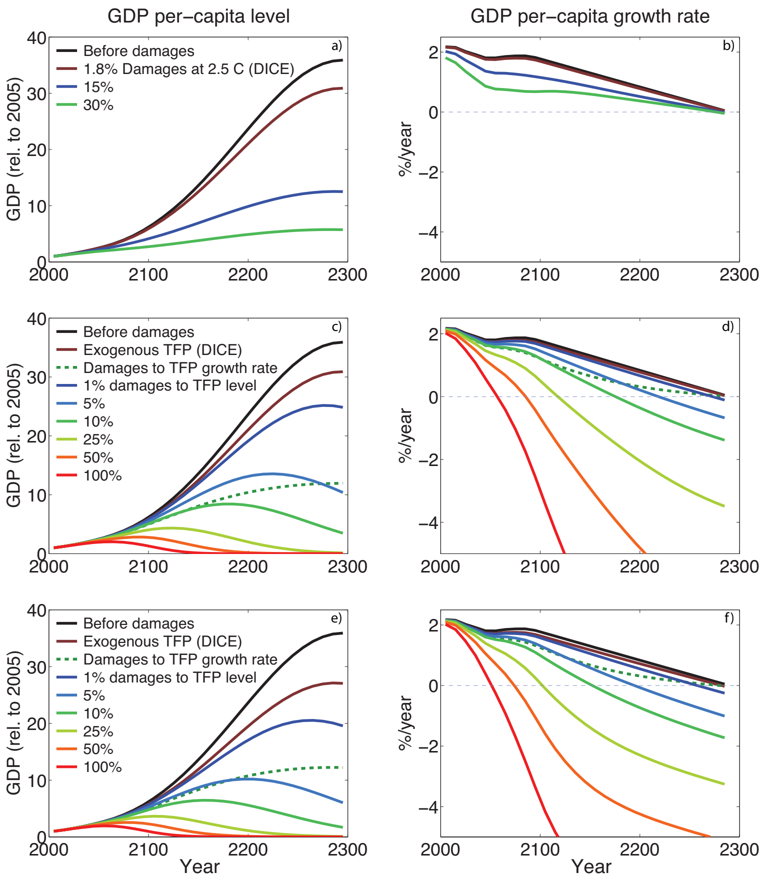

Fig. 4: Per capita economic output (left) and growth rates (right) in interagency DICE-IMAGE with a variety of climate damages representations. The no-climate-change case is repeated in black. (a-b): varying damages magnitude at 2.5 °C calibration point. Default IAWG value of 1.8% in brown. (c-d): damages applied to the TFP level and TFP growth rate. (e-f): repeat of c-d with modified model (endogenous emissions and improved carbon cycle). Model modifications produce slightly lower economic output in all but catastrophic cases, where reduced CO_2 emissions moderate climate change and reduce losses instead.

The results of this exercise suggest that uncertainty in SCC values due to treatment of damages is comparable to that due to treatment of discounting. SCC values rise approximately exponentially with fraction of damages to TFP. The rate of rise depends on η, with higher η producing greater sensitivity to damage assumptions: when damages are low and growth rates positive, harms to future generations are weighted less; when the economy contracts, harms to future generations are weighted more (Fig. 5). In all cases with damages to TFP levels, growth rates become negative and either produce negative discount rates or would do so if the analysis timeframe

Damages treatment	2010 SCC Value ($2007/tCO2)		
	IAWG model fixed discounting	*Modified model* $\eta = 2$, $\rho = 1\%$	*Modified model* $\eta = 1$, $\rho = 0.1\%$
DICE damages	34	16	210
1% damages to TFP level	51	22	440
5% damages to TFP level	110	54	1,300
Damages to TFP growth rate	160	72	1,500
10% damages to TFP level	160	130	2,200
25% damages to TFP level	250	1,600	4,800
50% damages to TFP level	320	100,000	8,000

Table 1: Selected 2010 SCC estimates from unmodified and modified interagency DICE-IMAGE (climate sensitivity 3°C/CO_2 doubling), under different formulations of climate damages and assumptions about discounting. Discounting with $\eta = 2$, $\rho = 1\%/yr$ produces greater sensitivity to damage treatment. With DICE damages, SCC is lower than in the fixed-discounting case because the endogenous discount rate is initially larger than 3%. Cases with damages to TFP eventually produce negative discount rates, so SCC estimates would grow if analysis were extended past 2300.

were extended. Once the discount rate is negative, the present value of future damages grows exponentially with the time until damages occur. The exact SCC value is therefore an artifact of the time horizon of the analysis and would increase with the length of time considered. The SCC values we show are several orders of magnitude higher than IAWG estimates, but even so are limited by termination of the analysis in 2300. Very high SCC values indicate large potential harms from climate change, but are difficult to interpret quantitatively.

The extreme cases of climate-related damages that we explore may not be realistic, as neither standard nor interagency DICE contains the flexibility to represent behavior in circumstances of economic contraction. Adjustments to savings rates do not alter the qualitative results, but our simple damage formulation may not realistically capture economic consequences given adaptive actions. The work here is simply an exploration of uncertainty across possible parameter values in the simple IAM frameworks commonly used. The importance of growth effects means that more realistic representations are needed.

5 Discussion and Conclusions

Our results imply that the SCC is far more uncertain than shown in the IAWG report or in previous modeling exercises, and that narrow distributions appear to be an artifact of model assumptions. Prior models do not allow the SCC to affect growth (except indirectly) and the SCC is sensitive to this restriction. While we take no view on whether climate change will affect growth, it is not likely that these effects can be ruled out a priori, and they should not be precluded by choices made in the structure of the model. If climate change reduces TFP levels or growth rate, the direction of

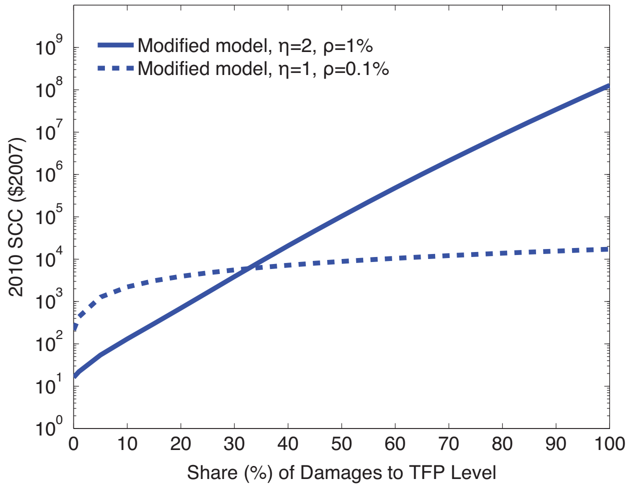

Fig. 5: The 2010 SCC from modified DICE under varying assumptions regarding damages to productivity, for two alternate specifications of discount rate: $\eta = 2$ and $\rho = 1\%$ (solid) and $\eta = 1$, $\rho = 0.1\%$ (dashed). The SCC rises exponentially with greater climate impacts to the determinants of growth. Higher η produces higher SCC values in simulations dominated by negative growth rates, because future harms are weighted more.

the changes in the SCC value are uniformly upward. It is therefore possible that the SCC was underestimated by the IAWG and by previous studies.

In the model studied here, even a modest impact of climate damages on productivity can cause the SCC to grow so large as to limit its usefulness as a guide to policymaking. The SCC is evaluated under business-as-usual assumptions, which assume no policy-driven mitigation. Incremental damages will be maximal in this case, because incremental losses grow with the degree of climate change. A large SCC value signifies large potential gains from mitigation, but if current mitigation is far from optimal, the SCC would exceed the value of a carbon tax in the context of a comprehensive policy. The optimal carbon tax is set instead to that point where the marginal mitigation costs are equal to the marginal benefits of reduced harms from climate change.[5] In the case of very high SCC values, formulating regulatory policy based on the SCC rather than the optimal tax would impose undue costs. (No sensible policymaker, for example, would apply an SCC value of \$100,000/tCO_2 in cost-benefit analysis if all emissions could be eliminated for \$100/tCO_2.)

Understanding how interactions between climate change and economic growth produce uncertainty in the SCC provides insight into past controversies over the appropriate choice of discount rate. Proponents of an “empirical” discount rate argue for use of values similar to observed market rates while proponents of an “ethical”

[5] The optimal carbon tax would be estimated by an analysis in which mitigation efforts are incrementally increased until the cost of any additional mitigation no longer exceeds the resulting additional benefit.

discount rate argue for lower values to place greater weight on the welfare of future generations. Our results suggest that the roots of the dispute may lie not in the principles of discounting but in differing implicit assumptions about climate damages combined with counterintuitive IAM behavior. A 3% discount rate means that harms after 2100 are essentially disregarded. But it is not unethical to disregard climate harms to future generations if those harms are small. The SCC values from the IAWG process are not unreasonable if the assumptions in the IAWG models are true, and future generations are many times richer despite climate change. If impacts are catastrophic instead, then standard economic analysis would indicate a low discount rate and would produce a recommendation of significant policy action. (See review in Kaplow et al, 2010). In this study, SCC values become very high if climate change reduces future wealth significantly by reducing the growth rate. It is possible that the debate over discounting results not from a difference in ethics but from an unrecognized dispute over the treatment of climate impacts.

Finally, our results suggest that the greatest uncertainty in the cost of climate change may lie not in the magnitude of losses at any given time but in how those losses affect growth. DICE damage magnitudes are broadly consistent with the estimate in the IPCC Fourth Assessment Report that a temperature change of 4 °C would cause global mean losses between 1 and 5% of GDP (Pachauri, 2007). Both the physical and social science communities have shown increasing interest in studying potential climate impacts, and many current studies focus on better quantifying economic losses. Our exploration of SCC sensitivities suggests that a higher research priority should be understanding how those losses relate to growth. The importance of growth is well understood more generally; even small differences in growth rates can produce large differences in wellbeing over time. As in the rest of economics, growth effects may be the predominant factor governing the impacts of climate change.

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

Online resources / supplementary materials

E.J. Moyer[1*], M.D. Woolley[2], M.J. Glotter[1], and D.A. Weisbach[3]

Contents

1 2013 update to the IAWG social cost of carbon estimates

The U.S. government's Interagency Working Group on the social cost of carbon released an updated set of SCC estimates in May 2013 IAWG (2013). The IAWG recalculated SCC values using updated versions of all three IAMs used in the original study (DICE, FUND, and PAGE), based new code releases by the models' original authors. The IAWG did not make any changes regarding the discount rates or method of discounting, the basecase economic scenarios (economic growth, population, and emissions), or climate sensitivity. Comparing SCC estimates between the two studies is made somewhat complicated by the fact that the SCC grows over time and the IAWG reported values for the year 2010 in the original report and 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, implying a modest real increase in SCC values (Figure OR1). The change does not qualitatively impact the conclusions and recommendations of this study. Model changes are summarized in detail, below.

The interagency DICE model was updated to reflect changes that appeared in the 2010 standard DICE version. Changes included a damage function that represents sea level rise separately from all other damages, and adjusted values for the carbon cycle model. The carbon 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. The new parameter values were calibrated to decrease the carbon uptake by the ocean, resulting in higher atmospheric carbon concentrations. We tested the new parameter

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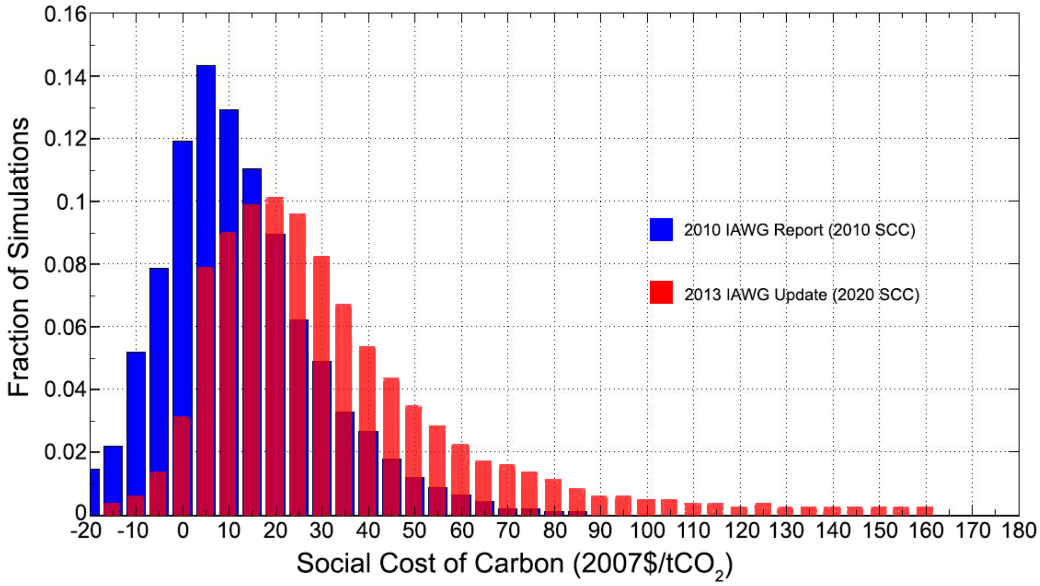


Figure OR1: Histogram of SCC estimates from the 2010 IAWG report (blue) and 2013 IAWG update (red) for the 3% discount rate case. Estimates sample across socioeconomic scenarios and climate sensitivity values. Values are digitized from Figure A8 of IAWG (2010) and from an unnumbered figure on p. 14 of IAWG (2013).

values in the original IAWG DICE model and confirmed that they result in slightly higher carbon concentrations. However, the carbon cycle changes do not prevent the excessive long-term uptake rates discussed in Section 5.3 and Glotter et al (2013), which result from failure to incorporate nonlinear ocean chemistry.

The new DICE damage function decomposes damages into two parts: one specific to sea level rise and one representing all other damages. Both of these of the new component damage functions model economic damages as a quadratic function of temperature change, as in the 2007 version. According to IAWG (2013), the effect of the change to the damage function is to increase overall damages 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.

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.

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

Because the SCC is an average of the outputs of all 3 IAMs, all model changes impacted the reported SCC estimates.

2 Romer model with climate damages to two sectors

In standard and interagency DICE, technological change is exogenously specified, and this specification drives the growth of the economy. Under this specification, even massive damages from climate change have little effect on long term growth if they merely reduce usable output. (See main text.) We consider how climate change damages would affect long-term growth in the framework of the simplest possible model of endogenous technical change, the model developed in Romer (1990). (We closely follow the statement of the model in Aghion and Howitt (2009).) In this model, the economy is divided into two sectors. A manufacturing sector uses labor and machines (or ideas) to produce usable output under conditions of perfect competition. A research or inventing sector produces machines or ideas that contribute to the manufacturing sector. The greater the variety of machines or ideas, the more efficient the manufacturing sector, so productivity arises as a function of market activities rather than being specified exogenously. We modify the model so that damages from climate change affect both the manufacturing and research sectors and consider how these damages affect growth.

As Romer discusses, the structure of the Romer (1990) model is closely related to that of the Solow-Swan model, which is used in DICE. Nevertheless, some of the assumptions may differ so the two are not directly comparable. We use the Romer (1990) model to motivate a damage function in DICE rather than as a formal derivation of such a function.

As a demonstration, we consider first a simple case where output is produced by the combination of labor and research in which research is a constant fraction γ of the economy. Research is represented by the sum of the total designs or ideas x indexed by i. This sum is combined with labor, L, and the output is reduced by harms from climate change leading to an output of:

$$y_t = (1-D)L\int_0^t x_i di, \tag{1}$$

where damages D are as in DICE. If research is a constant fraction γ of the economy, we can write $x_t = \gamma y_t$. The change in income over time is:

$$\frac{dy_t}{dt} = (1-D)L\gamma y_t, \tag{2}$$

and the growth rate is reduced by climate damages:

$$g_t = \frac{dy_t/dt}{y_t} = (1-D)L\gamma. \tag{3}$$

Thus, even in a very simple model, the growth rate can be reduced by harms from climate change.

The simple model above assumes that the fraction of the economy devoted to research is fixed, but the Romer (1990) model endogenizes this choice. In a world with climate change, the research sector may grow (or shrink) in response to that change. To check that the intuitions from the simple case considered above carry over, we turn to a modification of Romer (1990) to include harms from climate change.

We use the same objective function and utility function used in DICE (restated here in continuous time for simplicity):

$$W = \int_0^\infty \frac{c_t^{1-\eta}}{1-\eta} e^{-\rho t} dt, \tag{4}$$

where η is the elasticity of the marginal utility of consumption and ρ is the pure rate of time preference. Given this structure of preferences, the interest rate r must follow the Euler equation:

$$g = \frac{r - \rho}{\eta}, \tag{5}$$

where g is the growth rate of GDP.

DICE assumes that there is a single economic sector that combines capital and labor at productivity rate A_t to produce a final consumption good. Following Romer, we alter this assumption so that there are two sectors to the economy, a manufacturing sector which produces a final consumption good and a research sector which produces an intermediate good used in the production of the final good. The final good is the numeraire with price 1. Production of the intermediate good uses the final good as an input (along with labor) with units set so one unit of the final good is required to produce one unit of the intermediate good.

The intermediate good can be thought of as machines, blueprints, ideas, patents, or any other input into the production of the final good. We index the intermediate inputs i in the interval $[0, A_t]$ where A_t is the measure of the total number of intermediate good at time t. A_t is a measure of the variety of intermediate goods. A producer of an intermediate good is given a monopoly or a patent over that good but there is free entry into the research sector so expected profits are zero.

We assume that there is a fixed pool of labor divided into the final good sector (L_1) and the research sector (L_2). Total labor is $L = L_1 + L_2$. The restriction to a fixed pool of labor is not present in DICE. Although this assumption can be relaxed, following Jones (1995), for simplicity we retain the assumption here. We let damages reduce usable output as in DICE.

The production function for the final good combines labor (with share $1 - \alpha$) and the intermediate sector:

$$Y_t = (1 - D)L_1^{1-\alpha} \int_0^{A_t} x_i^{\alpha} di. \tag{6}$$

$\alpha \in [0, 1]$, and each x_i is the amount of intermediate product i used as input.

To see the relationship of this model to DICE, denote X_t as the total amount of the final good used to produce intermediate goods. X_t must be equal to the total intermediate output:

$$X_t = \int_0^{A_t} x_i di. \tag{7}$$

Under the assumption that an equal amount of each intermediate good i is used (shown to be true below), we can write $x = X_t/A_t$. Final output at time t is:

$$Y_t = (1 - D)A_t L_1^{1-\alpha} x^{\alpha}, \tag{8}$$

which closely resembles the production function in DICE except that the intermediate goods x function as the capital input.

GDP at time t is the output less the amount used to produce the intermediate good:

$$GDP_t = A_t \left[(1 - D)L_1^{1-\alpha} x^{\alpha} - x\right]. \tag{9}$$

The resulting growth rate along the balanced growth path is:

$$g = \frac{1}{A_t} \frac{dA_t}{dt}. \tag{10}$$

Our goal is to understand how damages from climate change reduce the growth rate of A_t, which is equivalent to understanding how they affect g. To do this, we write g in terms of the primitives of the model.

Start by solving for the production of the intermediate good. A producer of an intermediate good will maximize profits:

$$\Pi_i = p_i x_i - x_i, \tag{11}$$

where p_i is the price of the intermediate good i and recalling that the final good is used as an input to production of the intermediate good but that the price of a final good is equal to the price of one intermediate good. That is revenue is price times quantity and cost is equal to output given the one-for-one technology. The price p_i will be equal to the marginal product of the good in the final sector.

$$p_i = \frac{\partial Y_t}{\partial x_i} = (1-D)\alpha L_1^{1-\alpha} x_i^{\alpha-1}. \tag{12}$$

Substituting, we get

$$\Pi_i = (1-D)\alpha L_1^{1-\alpha} x_i^{\alpha} - x_i. \tag{13}$$

The monopolist researcher chooses x_i to maximize this expression. The first order condition is

$$\frac{\partial \Pi_i}{\partial x_i} = (1-D)\alpha^2 L_1^{1-\alpha} x_i^{\alpha-1} - 1 = 0. \tag{14}$$

The profit maximizing quantity therefore is

$$x_i = (1-D)^{\frac{1}{1-\alpha}} L_1 \alpha^{\frac{2}{1-\alpha}}. \tag{15}$$

It follows that the equilibrium quantity will be the same in every sector i, so we can drop the subscripts where convenient. The equilibrium profit flow is:

$$\Pi = \frac{1-\alpha}{\alpha} x. \tag{16}$$

The key modeling choice made by Romer is that the growth of the output of the research sector grows in proportion to the existing stock in that sector, creating knowledge spillovers. If there is a constant productivity in the research sector of λ, Romer writes $dA_t/dt = \lambda L_2 A_t$. The key question here is whether climate change reduces the flow of research or intermediate machines over time. We impose an assumption that climate change reduces the flow of research similarly to how it reduces usable output. That is, we assume that climate change hurts both sectors of the economy. Therefore, the stock of intermediate machines evolves according to:

$$dA_t/dt = (1-D)\lambda L_2 A_t. \tag{17}$$

Because the research sector is monopolistically competitive (there is free entry), the flow of profits must be zero. If the wage rate paid to researchers is w_t the flow of profits to the research sector is

$$\frac{\Pi}{r}(1-D)\lambda A_t L_2 - w_t L_2 = 0. \tag{18}$$

The first term is the output of the the sector, $(1-D)\lambda A_t L_2$, multiplied by the price of each machine or idea (the present value of profits, Π/r). Solving,

$$r = (1-D)\lambda A_t \Pi / w_t. \tag{19}$$

We need to solve for the equilibrium wage rate. This will be equal to the marginal product of labor, so we get:

$$w_t = \frac{\partial Y_t}{\partial L_1} = (1-D)(1-\alpha)L_1^{-\alpha} A_t x^{\alpha}. \tag{20}$$

Using equation (15), we get

$$w_t = (1-D)^{\frac{1}{1-\alpha}}(1-\alpha)\alpha^{\frac{2\alpha}{1-\alpha}} A_t. \tag{21}$$

Substituting, we get an expression for the interest rate:

$$r = (1-D)\lambda L_1 \alpha. \tag{22}$$

Since

$$g = \frac{1}{A_t}\frac{dA_t}{dt} = (1-D)\lambda L_2 = (1-D)\lambda(L-L_1), \tag{23}$$

we get

$$r = \alpha\left[g - (1-D)\lambda L\right], \tag{24}$$

and substituting this expression into the Euler equation (5) we get

$$g = \frac{\alpha\lambda L(1-D) - \rho}{\alpha + \eta}. \tag{25}$$

Climate damages in this formulation reduce the growth rate. The key assumption is that they reduce the flow of output in the research sector in exactly the same way that they reduce the flow of output in the manufacturing sector. If we allow harms to the research sector to differ, the model would be identical except that equation (25) would be reduced by a different damage function $(1-D_2)$ where D_2 can be different from D. We have no views on the appropriate damage function in the research sector and impose the same damage function merely as a baseline.

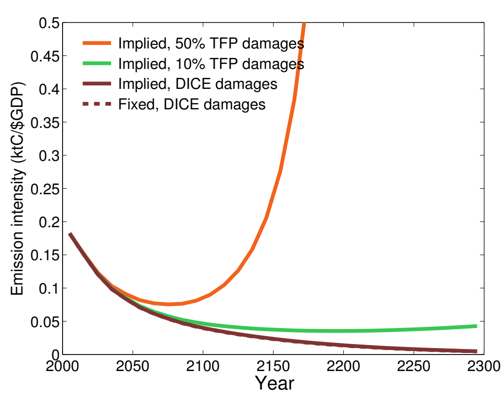
The damage function used in the text is based on equation (25). Recall that we want an expression for the growth rate of A_t, but this is just g in this model. We simplify by setting $\rho = 0$. The growth rate of A_t is then reduced by the damages $(1-D)$, as we specified in the text. Moreover, output is also reduced by damages, as in equation (6).

3 Model modification: endogenous emissions

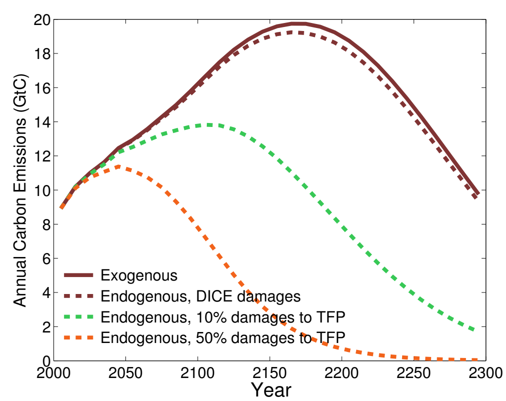
The IAWG process specified fixed emissions paths decoupled from actual economic performance. (In the IMAGE scenario, emissions increase for ∼150 years and decline thereafter, presumably driven by some assumed technological change). If the economy in a model simulation declines, however, retaining a fixed path of emissions would imply 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. For example, in a damages formulation where 50% of damages apply to TFP, assuming a fixed emissions path means that implied emissions intensity rises by approximately a factor of five by the year 2150 (Figure OR2a). This result does not appear to be intended by the IAWG, and it appears to arise only in scenarios they did not consider. Using exogenous emissions in simulations with economic decline would lead to overstating the SCC because emissions continue their basecase evolution even if the economy contracts, leading to sustained high climate damages.

To avoid this problem, we assume a fixed trajectory of emissions *intensity* rather than emissions, deriving it from the basecase runs in the IAWG model (which has ktC/GDP dropping from a current rate of 0.18 to 0.04 in 2100). We then calculate emissions endogenously based on economic activity in a given scenario and the assumed emissions intensity. In cases where a high percentage of damages apply to TFP, the difference is significant: in the example above, adjusted carbon emissions in the year 2100 are approximately half those in the basecase emissions path.

We take no position on the plausibility of the emissions pathway itself, which implies that CO_2 emissions would decline steeply even in the absence of mitigation policies. As the purpose of this study is to examine only the effects of climate impacts on growth, and IAWG emissions scenarios are broadly similar, we simply take the IMAGE scenario as fixed. Uncertainty in the pathway of technological change would produce additional uncertainty in SCC values.



(a) Emission intensity assumptions



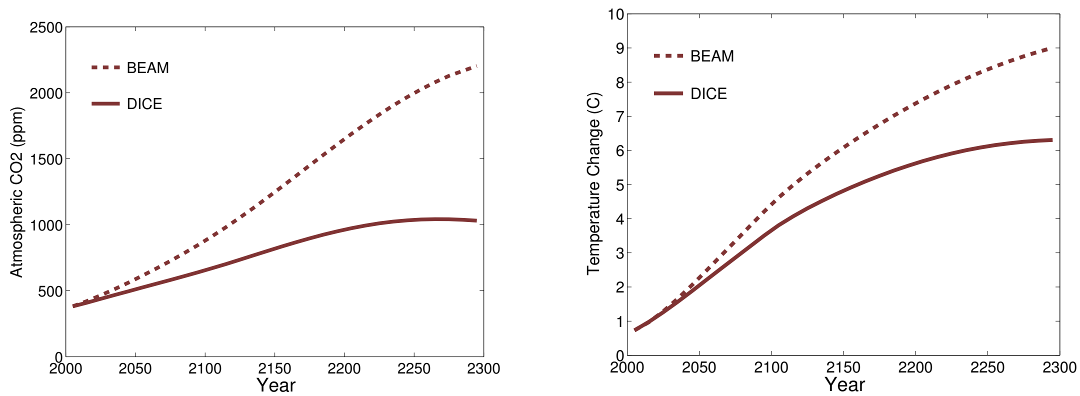
(b) Emission paths

Figure OR2: Emissions intensity (left) and annual emission levels (right), under alternative modeling assumptions. Interagency DICE assumes an exogenous emission level (solid brown, right), yielding an implied emissions intensity (solid brown, left). Employing a fixed emissions path under alternative damage scenarios leads to differing implied emissions intensities (solid green and solid orange, left panel). Alternatively, we fix emissions intensity (dashed brown, left) and derive implied endogenous emissions for the various damage scenarios shown (dashed green and dashed orange, right). This formulation is consistent with the original DICE model.

4 Model modification: physical carbon cycle

IAMs that do not produce economic contraction need only a rudimentary representation of the physical climate system. Persistent growth would indicate use of a high discount rate in SCC calculations, making long-term climate changes irrelevant because long-term harms are disregarded in the analysis. If however climate losses in an IAM produce low or even negative growth rates and resulting low or negative endogenous discount rates, the modeled climate representation must remain accurate at long timescales, because the effects of climate change in the distant future matter. The carbon cycle in standard and interagency DICE approximates real-world physics only on short timescales: it provides reasonable representation for about 50 years but then deviates strongly from the predictions of state-of-the-art coupled climate models. Atmospheric CO_2 perturbations in DICE disappear within centuries while larger models show them persisting on the order of 10,000 years (Archer et al, 2009; Glotter et al, 2013). Adjustment of the carbon cycle parameters in the 2010 DICE update used in IAWG (2013) do not fix this fundamental issue.

Errors in CO_2 evolution arise in DICE because the model uses a linear representation of ocean carbon uptake. In the real world, ocean carbonate chemistry makes CO_2 uptake nonlinear. At present, the ocean contains over 100 times as much dissolved inorganic carbon as 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). Without this nonlinear chemistry, the DICE carbon cycle produces too-rapid removal of atmospheric CO_2 perturbations. For the IMAGE emissions scenario, the 2007 DICE carbon cycle model yields a rise in atmospheric CO_2 concentrations by the year 2300 only a third as large as would be predicted by more realistic models (Figure OR3a). DICE underestimates CO_2 in 2300 by over 1000 ppm and warming by nearly 3°C (Figure OR3b). To correct this problem, we use a simple carbon cycle model based on Bolin and Eriksson (1959) with nonlinear chemistry as described in Revelle and Suess (1957). The "BEAM" (Bolin and Eriksson Adjusted Model) representation is described and validated in Glotter et al (2013).



(a) CO_2 concentration

(b) Mean temperature change

Figure OR3: Carbon dioxide concentration (a) and global mean temperature change (b) using the BEAM (dashed) and DICE (solid) carbon cycle models in interagency DICE-IMAGE. The DICE CO_2 trajectory and resulting projected temperature anomalies vary substantially from those produced with the more physically realistic BEAM. Temperature change in DICE is benchmarked from the pre-industrial, so the year 2000 already experiences ~ 0.8°C global temperature rise.

5 Endogenous discounting in modified IAWG-DICE

The IAWG protocol specified a fixed discount rate of 3% following OMB guidelines (Circular A-4, which prescribes the required procedures for cost-benefit analysis). However, a requirement of a fixed, exogenous discount rate does not make sense if growth declines substantially or is negative because of harms from climate change. Although there is significant dispute about discounting in climate change policy assessments (see summary in Kaplow et al, 2010), under all formulations, a higher growth rate implies a higher discount rate and a lower growth rate implies a lower one.

The implied interest rate in the standard DICE model is given by the Ramsey equation:

$$r_t = \eta \cdot g_t + \rho, \tag{26}$$

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). Commentators differ widely on how to set η and ρ, but all agree that a lower growth rate should imply a lower discount rate. A fixed 3% discount rate when growth is low or negative is unlikely to reflect the implied discount rate in DICE for any reasonable choice of η and ρ. We therefore use equation 26 to compute an endogenous discount rate.

The choice of values for η and ρ is controversial, and we take no view on the correct values here. We consider two options. The first sets $\eta = 2$ and $\rho = 1\%/\text{yr}$, values consistent with many previous studies. (See discussion on p. 21-23 of IAWG (2010); standard DICE (Nordhaus, 2007) uses $\eta = 2$ and $\rho = 1.5\%/\text{yr}$.) As an alternative, we consider the lower values used in the Stern Report: $\eta = 1$ and $\rho = 0.1\%/\text{yr}$ (Stern, 2007). We show the effect of both choices on SCC estimates in Figure 5.

The two discounting parameter choices bracket the OMB-required 3% discount rate when applied to the basecase economic trajectories. Basecase economic growth under DICE damages (Figure 2) involves growth rate slowing from 2.2%-0% in the two centuries from 2000-2300. Resulting discount rates would evolve from 5.4%-1% using the higher η and ρ values and from 2.3%-0.1% using the lower ones.

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