Revisiting the social cost of carbon

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The social cost of carbon (SCC) is a central concept for understanding and implementing climate change policies. This term represents the economic cost caused by an additional ton of carbon dioxide emissions or its equivalent. The present study presents updated estimates based on a revised DICE model (Dynamic Integrated model of Climate and the Economy). The study estimates that the SCC is \$31 per ton of CO_2 in 2010 US\$ for the current period (2015). For the central case, the real SCC grows at 3% per year over the period to 2050. The paper also compares the estimates with those from other sources.

social cost carbon | climate change | economics | DICE model

The most important single economic concept in the economics of climate change is the social cost of carbon (SCC). This term designates the economic cost caused by an additional ton of carbon dioxide emissions or its equivalent. In a more precise definition, it is the change in the discounted value of economic welfare from an additional unit of CO_2-equivalent emissions.

The SCC has become a central tool used in climate change policy, particularly in the determination of regulatory policies that involve greenhouse gas emissions (1, 2). Estimates of the SCC are necessarily complex because they involve the full range of impacts from emissions, through the carbon cycle and climate change, and including economic damages from climate change. At present, there are few established integrated assessment models (IAMs) that are available for estimation of the entire path of cause and effect and can therefore calculate an internally consistent SCC. The DICE model (Dynamic Integrated model of Climate and the Economy) is one of the major IAMs used by scholars and governments for estimating the SCC. Up to now, the most recent full-model estimates have been with the DICE-2013R model (2).

The present study presents the results of a fully revised version of the DICE model (as of 2016). This is the first major revision since the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). This article describes the changes in the model from the last round, presents updated estimates of the SCC, partitions the changes in the SCC from 2013 to 2016 into the different parts of the model that have changed, and compares the new estimates with other models. The major result is a substantial increase in the estimated SCC.

Structure of the DICE-2016R Model

Background on the DICE Model. The analysis begins with a discussion of the DICE-2016R model, which is a revised version of the DICE-2013R model (1, 3). It is the latest version of a series of models of the economics of global warming developed in collaboration with colleagues at Yale University. The first version of the global dynamic model was in ref. 4. The discussion explains the major modules of the model, and describes the major revisions since the 2013 version. (The current version of the DICE-2016R is available at www.econ.yale.edu/~nordhaus/homepage/DICEmodels09302016.htm.)

The DICE model views climate change in the framework of economic growth theory. In a standard neoclassical optimal growth model known as the Ramsey model, society invests in capital goods, thereby reducing consumption today, to increase consumption in the future. The DICE model modifies the Ramsey model to include climate investments, which are analogous to capital investments in the standard model. The model contains all elements from economics through climate change to damages in a form that attempts to represent simplified best practice in each area.

Equations of the DICE-2016R Model. Most of the analytical background is similar to that in the 2013R model, and, for details, readers are referred to ref. 3. Major revisions are discussed as the equations are described.

The model optimizes a social welfare function, W, which is the discounted sum of the population-weighted utility of per capita consumption. The notation here is that V is the instantaneous social welfare function, U is the utility function, $c(t)$ is per capita consumption, and $L(t)$ is population. The discount factor on welfare is $R(t) = (1+\rho)^{-t}$, where ρ is the pure rate of social time preference or generational discount rate on welfare.

$$W = \sum_{t=1}^{T\max} V[c(t),\ L(t)]R(t) = \sum_{t=1}^{T\max} U[c(t)]L(t)R(t). \qquad [1]$$

The utility function has a constant elasticity with respect to per capita consumption of the form $U(c) = c^{1-\alpha}/(1-\alpha)$. The parameter α is interpreted as generational inequality aversion.

Net output is gross output reduced by damages and mitigation costs,

$$Q(t) = \Omega(t)[1-\Lambda(t)]Y(t). \qquad [2]$$

In this specification, $Q(t)$ is output net of damages and abatement, and $Y(t)$ is gross output, which is a Cobb–Douglas function of capital, labor, and technology. Total output is divided between total consumption and total gross investment. Labor is proportional to population, whereas capital accumulates according to an optimized savings rate.

Significance

The most important single economic concept in the economics of climate change is the social cost of carbon (SCC). At present, regulations with more than \$1 trillion of benefits have been written for the United States that use the SCC in their economic analysis. The DICE model (Dynamic Integrated model of Climate and the Economy) is one of three integrated assessment models used to estimate the SCC in the United States. The present study presents updated estimates based on a revised DICE model (DICE-2016R). The study estimates that the SCC is \$31 per ton of CO_2 in 2010 US\$ for the current period (2015). This study will be an important step in developing the next generation of estimates of the SCC in the United States and other countries.

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The current version develops global output in greater detail than earlier versions. The global output concept is purchasing power parity (PPP) as used by the International Monetary Fund (IMF). The growth concept is the weighted growth rate of real gross domestic product (GDP) of different countries, where the weights are the country shares of world nominal GDP using current international dollars. We constructed our own version of world output, and this corresponds closely to the IMF estimate of the growth of real output in constant international (PPP) dollars. The earlier model used the World Bank growth figures, but the growth rates by region could not be replicated.

The present version substantially revised both the historical growth estimates and the projections of per capita output growth. Future growth is based largely on a survey of experts conducted by Peter Christensen and colleagues at Yale University. Growth in global per capita output over the 1980–2015 period was 2.2% per year. Growth in global per capita output from 2015 to 2050 is projected at 2.1% per year, whereas that to 2100 is projected at 1.9% per year. The revisions are updated to incorporate the latest output, population, and emissions data and projections. Population data and projections through 2100 are from the United Nations. CO_2 emissions are from the Carbon Dioxide Information Analysis Center and are updated using various sources. Non-CO_2 radiative forcings for 2010 and projections to 2100 are from projections prepared for the IPCC Fifth Assessment.

The additional variables in the production function are $\Omega(t)$ and $\Lambda(t)$, which represent the damage function and the abatement cost function, respectively. The abatement cost function, $\Lambda(t)$ in Eq. **2**, was recalibrated to the abatement cost functions of other IAMs as represented in the Modeling Uncertainty Project (MUP) study (5). The result was a slightly more costly abatement function than earlier estimates.

The damage function is defined as $\Omega(t) = D(t)/[1 + D(t)]$, where

$$D(t) = \varphi_1 T_{AT}(t) + \varphi_2 [T_{AT}(t)]^2. \qquad \textbf{[3]}$$

Eq. **3** describes the economic impacts or damages of climate change, which is a key component in calculating the SCC. The DICE-2016R model takes globally averaged temperature change (T_{AT}) as a sufficient statistic for damages. Eq. **3** assumes that damages can be reasonably well approximated by a quadratic function of temperature change.

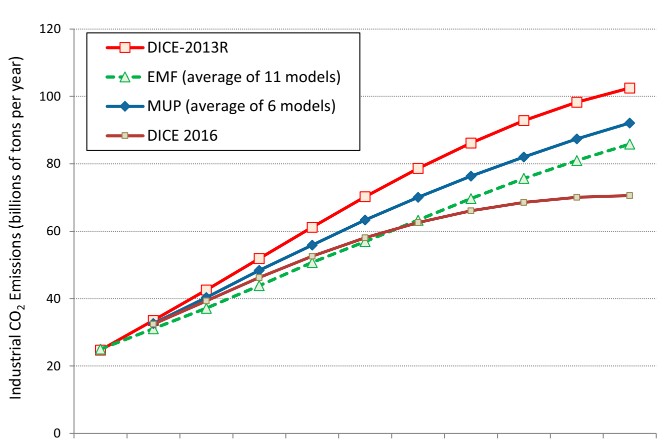

Fig. 1. Projected industrial CO_2 emissions in baseline scenario. The figure compares the projections of the most recent DICE models and two model comparison exercises. The estimates from the MUP project are from ref. 5, and the EMF-22 estimates are from ref. 14.

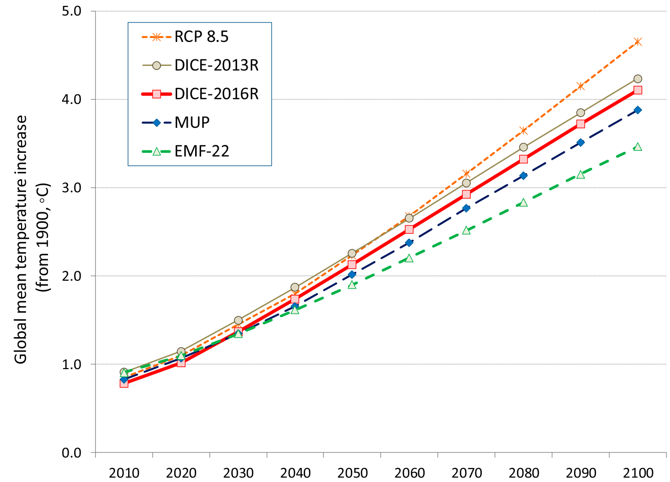

Fig. 2. Global mean temperature increase as projected by IPCC scenarios and integrated assessment economic models. The figure compares the projections of the most recent DICE models, the IPCC RCP high scenario (RCP 8.5), and two model comparison exercises.

The damage function was revised in the 2016 version to reflect new findings. The 2013 version relied on estimates of monetized damages from ref. 6. It turns out that that survey contained several numerical errors (7). The current version continues to rely on existing damage studies, but these were collected by Andrew Moffat and the author and independently verified (see *Supporting Information* for details). Including all factors, the final estimate is that the damages are 2.1% of global income at a 3 °C warming, and 8.5% of income at a 6 °C warming.

Uncontrolled industrial CO_2 emissions are given by a level of carbon intensity, $\sigma(t)$, times gross output. Total CO_2 emissions, $E(t)$, are equal to uncontrolled emissions reduced by the emissions reduction rate, $\mu(t)$, plus exogenous land-use emissions.

$$E(t) = \sigma(t)[1 - \mu(t)]Y(t) + E_{Land}(t). \qquad \textbf{[4]}$$

The model has been revised to incorporate a more rapid decline in the CO_2–output ratio to reflect the last decade's observations. The decade through 2010 showed relatively slow decarbonization, with the global CO_2/GDP ratio changing at −0.8% per year. However, the most recent data indicate a sharp downward tilt, with the global CO_2/GDP ratio changing at −2.1% per year over the 2000–2015 period (preliminary data). Whether this is structural or the result of climate policies is unclear at this point. For the DICE model, we assume that the rate of decarbonization going forward is −1.5% per year (using the IMF output concept).

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

$$M_j(t) = \phi_{0\,j} E(t) + \sum_{i=1}^{3} \phi_{i\,j} M_i(t-1). \qquad \textbf{[5]}$$

The three reservoirs are $j = AT$, UP, and LO, which are the atmosphere, the upper oceans and biosphere, and the lower oceans, respectively. The parameters $\phi_{i\,j}$ represent the flow parameters between reservoirs per period. All emissions flow into the atmosphere. The 2016 version incorporates new research on the carbon cycle. Earlier versions of the DICE model were calibrated to fit the short-run carbon cycle (primarily the first 100 y). Because we plan to use the model for long-run estimates, such as the impacts on the

Table 1. Global SCC by different assumptions

Scenario	Assumption	2015	2020	2025	2030	2050
Base parameters						
	Baseline*	31.2	37.3	44.0	51.6	102.5
	Optimal controls†	30.7	36.7	43.5	51.2	103.6
2.5 degree maximum						
	Maximum†	184.4	229.1	284.1	351.0	1,006.2
	Max for 100 y†	106.7	133.1	165.1	203.7	543.3
The Stern Review discounting						
	Uncalibrated†	197.4	266.5	324.6	376.2	629.2
Alternative discount rates*						
	2.5%	128.5	140.0	152.0	164.6	235.7
	3%	79.1	87.3	95.9	104.9	156.6
	4%	36.3	40.9	45.8	51.1	81.7
	5%	19.7	22.6	25.7	29.1	49.2

The SCC is measured in 2010 international US dollars.
*Calculation along the reference path with current policy.
†Calculation along the optimized emissions path.

melting of large ice sheets, it was decided to change the calibration to fit the atmospheric retention of CO_2 for periods up to 4,000 y. Based on ref. 8, the 2016 version of the three-box model does a much better job of simulating the long-run behavior of larger models with full ocean chemistry. This change has a major impact on the estimate of the SCC (see Table 4 below).

The relationship between GHG accumulations and increased radiative forcing is shown in Eq. **6**.

$$F(t) = \eta\{\log_2[M_{AT}(t)/M_{AT}(1{,}750)]\} + F_{EX}(t). \quad [6]$$

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

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

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

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

In these equations, $T_{AT}(t)$ is the global mean surface temperature and $T_{LO}(t)$ is the mean temperature of the deep oceans.

The climate module has been revised to reflect recent Earth system models. We have set the equilibrium climate sensitivity (ECS) using the analysis in ref. 9. Ref. 9 uses a Bayesian approach, with a prior based on previous studies and a likelihood based on observational or modeled data. The reasons for using this approach are provided in ref. 5. The final estimate is mean warming of 3.1 °C for an equilibrium CO_2 doubling. We adjust the transient climate sensitivity (TCS) (sometimes called the transient climate response) to correspond to models with an ECS of 3.1 °C, which produces a TCS of 1.7 °C.

The treatment of discounting is identical to that in DICE-2013R. We always distinguish between the welfare discount rate (ρ) and the goods discount rate (r). The welfare discount rate applies to the well-being of different generations, whereas the goods discount rate applies to the return on capital investments. The former is not observed, whereas the latter is observed in markets. When the term "discount rate" is used without a modifier, this will always refer to the discount rate on goods.

The economic assumption behind the DICE model is that the goods discount rate should reflect actual economic outcomes; this implies that the assumptions about model parameters should generate savings rates and rates of return on capital that are consistent with observations. With the current calibration, the discount rate (or, equivalently, the real return on investment) averages 4¼% per year over the period to 2100. The discount rate is the global average of a lower figure for the United States and a higher figure for other countries and is consistent with estimates in other studies that use US data. (This specification is sometimes called the "descriptive approach" to discounting. The alternative approach, used in ref. 10 and elsewhere, is called the "prescriptive discount rate." Under this second approach, the discount rate is assumed on a normative basis and determined largely independently of actual market returns on investments.)

Major Results for DICE-2016R

It will be useful to show some representative results from the revised model. We also compare the results with other models and studies. Fig. 1 shows the projected industrial emissions of CO_2 over the coming century. DICE-2016R is at the low end of different projections after midcentury. The reason (as explained

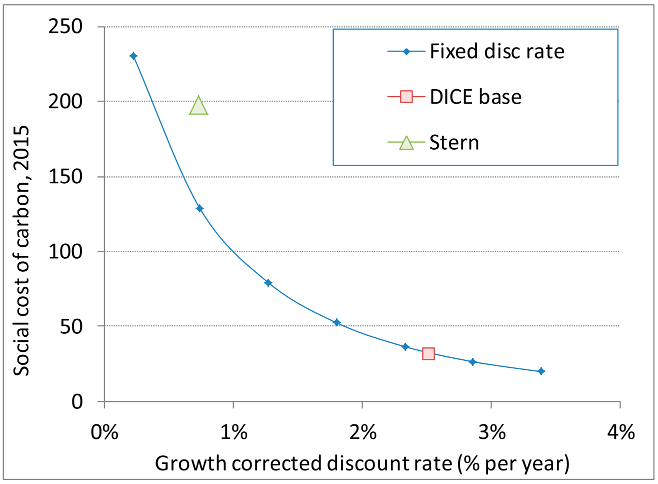

Fig. 3. Social cost of carbon and growth-corrected discount rate in DICE model. The growth-corrected discount rate equals the discount rate on goods minus the growth rate of consumption. The solid line shows the central role of the growth-corrected discount rate on goods in determining the SCC in the DICE model. The square is the SCC from the full DICE model, and the triangle uses the assumptions of *The Stern Review* (10). A further discussion and derivation of the growth-corrected discount rate is given in *Supporting Information*.

Table 2. Regional SCC

Region	SCC 2015, \$/tCO_2, 2010 \$	RICE 2010, % global	FUND 2013, % global	PAGE 2011, % global	This study, % global
United States	4.78	10	17	7	15
EU	4.79	12	24	9	15
Japan	1.07	2	3	na	3
Russia	0.91	1	10	na	3
Eurasia	1.56	1	na	na	5
China	6.61	16	8	11	21
India	2.93	12	5	22	9
Middle East	2.16	10	na	na	7
Africa	1.03	11	6	26	3
Latin America	1.87	7	na	11	6
Other high income	1.00	4	na	na	3
Other	2.50	12	[28]	[16]	8
Global	31.21	100	100	100	100

This table distributes the global SCC from Table 1 by region. The first and last columns assume that the SCC is proportional to the discounted value of output in each region over the 2020–2050 period, discounted at a discount rate of 5% per year. na, not available in the source document; tCO_2, metric tons of CO_2. Brackets around estimates are total of omitted regions.

in the discussion of Eq. **4**) is that the rate of decarbonization has increased in recent years. The lower emissions trend is reflected in the 2016 DICE version but not in most other model projections, which often reflect models constructed several years ago.

Fig. 2 shows the projected temperature trajectories in five different approaches. The results for DICE-2016R are in the middle of the pack after all of the different revisions are included. The DICE results are above those of the Energy Modeling Forum 22 (EMF-22) exercise as well as the central projections from the MUP project (5). The top line is the ensemble average from the Fifth Assessment Report of the IPCC (11) for the Representative Concentration Pathway (RCP) 8.5 scenario. However, the IPCC Representative Concentration Pathway (RCP) 8.5 projection has a higher radiative forcing than the baseline DICE-2016R model. Thus the summary is that the DICE temperature projection is roughly unchanged from the last version and is consistent (although a little lower) than the IPCC RCP8.5 ensemble average.

Estimates of the SCC

Definition of the SCC. Solving Eqs. **1**–**8** by optimizing the social welfare function (W) yields a path of all variables. We then define the SCC at time t as

$$\mathrm{SCC}(t) \equiv \frac{\partial W}{\partial E(t)} \Big/ \frac{\partial W}{\partial C(t)} \equiv \partial C(t)/\partial E(t). \qquad \textbf{[9]}$$

Looking at the middle term, the numerator is the marginal welfare impact of emissions at time t, and the denominator is the marginal welfare impact of a unit of aggregate consumption in period t; this gives the third term of Eq. **9**, in which the SCC equals the economic impact of a unit of emissions in terms of t-period consumption as a numéraire. In actual calculations, we take a discrete approximation to Eq. **9**. Note that the SCC is time-indexed because the marginal damage of emissions changes over time.

We have estimated the SCC in the DICE-2016R model for several alternative scenarios. These scenarios reflect differing assumptions about policy and discounting. The units are 2010 US international dollars (that is, in PPP) per metric ton of CO_2 and are expressed in terms of consumption in the given year.

SCC for Standard DICE Model Parameters. The central cases for the SCC are shown in the first two rows of Table 1. The first row shows the estimate for the standard DICE model with baseline or current climate policy. The SCC figure here is \$31.2 per ton of CO_2 for emissions in 2015, with the value rising at 3% per year in real terms through 2050. The SCC along an optimized path, shown in row 2, is

Table 3. Estimates of SCC for 2020 from US Interagency Working Group and comparison with DICE model in 2010 US\$

Model and scenario	5% per year discount rate on goods	DICE	4% per year discount rate on goods	3% per year discount rate on goods	2.5% per year discount rate on goods
Estimates of 2020 SCC from US Working Group, 2013 (2010\$)					
DICE-2010	12	na	na	40	59
PAGE	23	na	na	74	105
FUND	3	na	na	22	37
Average	13	na	na	**45**	67
Estimates for different DICE model versions (2010\$)					
DICE-2013R	15	24	26	50	74
DICE-2016R	23	**37**	41	87	140

Upper rows show estimates of the 2020 SCC from the IAWG. The three models have harmonized outputs, emissions, populations, and ETS distribution and use constant discount rates. Lower rows show the results of the estimates from the two latest versions of the DICE model for the baseline (Table 1) and using constant discount rates.

slightly lower than the baseline path. The difference between the two cases is small because marginal damages change relatively little between the optimal and baseline case.

Alternative Estimates. Table 1 shows alternative estimates. We show a calculation for constraining temperature to a 2½ °C limit in two cases: one with a hard cap of 2½ °C, and the second where that cap is for an average of 100 y rather than a single period. The average would be a more sensible objective if damages are a function of average rather than peak temperature. (The hard cap is infeasible for a maximum of 2 °C and would only be feasible if technologies were available that allow substantial negative emissions by around 2050.) The SCCs for the two limit cases are $184 and $107 per ton of CO_2 in 2015 for the two cases of maximum and average limit.

It is well known that the discount rate has an important impact on the SCC. A closer look shows that the key variable is the "growth-corrected discount rate," which is the difference between the discount rate on goods and the rate of growth of output (see *Supporting Information* and ref. 2). The estimates of the SCC with different discount rates on goods are shown at the bottom of Table 1. Table 1 also shows the SCC for the discounting procedure proposed in ref. 10. The relationship between the growth-corrected discount rate and the SCC is shown in Fig. 3.

Regional SCCs. A few IAMs disaggregate the global SCC into the regional SCCs. These regional estimates represent the marginal damages of emissions for a particular country or region, that is, the SCC when only the damages to that particular region are included in the calculation. These estimates are important for understanding the impacts on individual regions as well as the problem of noncooperative behavior. (In noncooperative behavior, national efforts will be determined by the national SCCs rather than the global SCC and will therefore be much lower; see ref. 12.) Table 2 shows four different sets of estimates of the regional composition of the SCC. The first three are from the three models used by the Interagency Working Group on Social Cost of Carbon (IAWG), and the fourth shows an estimate based on the discounted value of GDP of the regions. One point is clear: The regional estimates are poorly understood, often varying by a factor of 2 across the three models. Moreover, regional damage estimates are highly correlated with output shares ($R = 0.71$).

The dollar estimates of regional SCCs shown in the first numerical column of Table 2 allocate the global SCC based on the output shares. This estimate is used partially because the regional damage estimates are both incomplete and poorly understood. Additionally, regional output shares are well defined and easy to replicate and, in most cases, fall within the estimates of the different models. A key message here is that there is little agreement on the distribution of the SCC by region—except for the important point that each country's SCC is well below the global total.

Comparison with the IAWG. The US government has relied on the work of the IAWG to develop estimates of the SCC (see ref. 13 for different versions). The IAWG concept is conceptually comparable to the baseline in the first row of Table 1. The IAWG combines estimates from three models and multiple scenarios. Table 3 compares the latest round of estimates of the IAWG with estimates from the DICE-2013R and DICE-2016R models for the baseline model and different discount rates. The preferred SCC estimate of the most recent DICE model is about one-fifth lower than the IAWG's preferred SCC. At comparable discount rates, the DICE model estimate would be roughly twice that of the IAWG.

Uncertainty About the SCC

The central estimates in Tables 1–3 use the expected values of the parameters such as productivity growth. Developing reliable estimates that incorporate uncertainty has proven extremely challenging on both methodological and empirical grounds (5). Two major sources of uncertainty about the SCC are "model uncertainty" and "structural uncertainty." The difference across models in Table 3 shows model uncertainty. These estimates actually underestimate model uncertainty because they have been harmonized by the IAWG for several inputs (discounting, outputs, and temperature sensitivities) but retain differences in other model structures (particularly damage functions). Model uncertainty is more than a factor of 3 for the IAWG's preferred 3% discount rate.

Structural uncertainty, or uncertainty within models, arises from imprecision in knowledge of structural parameters or variables. The MUP project (5) was the first study to developed harmonized estimates of uncertainties of different models for a variety of models. I replicated the MUP methodology to estimate structural uncertainty about the SCC in the DICE model arising from three sources: productivity growth, equilibrium temperature sensitivity (ETS), and the damage function. The exact approach is described in *Supporting Information*.

That calculation provides an estimated SD of the SCC in 2015 of $32 per ton of CO_2. The 10th to 90th percentile range of the SCC for 2015 is $7 to $77. The IAWG estimates that the ratio of the 95th percentile to the average is 3.0, whereas the current estimate is a ratio of 2.8. Because the IAWG includes only uncertainty about the ETS, it is surprising that the IAWG uncertainty bounds are higher than those in the current model. These estimates confirm that there is extremely large structural uncertainty about the SCC even in a single model.

Accounting for the SCC Changes Since DICE-2013R

The estimated SCC has increased substantially since the last version, as shown in Table 3. We can decompose the changes by introducing each of the major components one by one. Table 4 accounts for the changes by major revision variable. Other than the adjustment of the damage function, other major changes had the effect of increasing the SCC between 2013 and 2016. The two major changes were the carbon cycle (discussed above) and estimated economic activity.

The reasons for the changes in economic estimates are important to understand. Data revisions have tended to increase measured output because statisticians "find" more output, and because of methodology changes. One important change has been from the movement among IAMs from market exchange rates (MER) (typical in models a decade ago) to PPP. As an example, estimated nominal world output in 2005 with MER was $46 trillion in the 2006 IMF database. In the 2016 estimate using PPP, world output in 2005 was $67 trillion, or 50% higher. Because damages are generally proportional to output, increasing output increases the SCC in a proportional fashion.

Table 4. Accounting for changes in SCC from DICE-2013R

Version	Model	SCC (2015), 2010 $	Change, %
1	Dice-2016	31.23	
2	1 + old damages	35.63	14
3	2 + old population	33.36	−6
4	3 + old temp sensitivity	30.58	−8
5	4 + old economics	21.25	−31
6	5 + old carbon cycle	16.01	−25
7	DICE-2013R	17.03	6

The table shows the impact of introducing model changes starting with the 2016 model and ending with the 2013 model in a step fashion. The last column shows the change moving from a later specification to an earlier one. A negative number in the last column is a decrease from 2016 to 2013. For example, introducing "old economics" in version 5 lowers the SCC by 25% relative to DICE-2016. The two major changes are economic assumptions and the carbon cycle (see *Accounting for the SCC Changes Since DICE-2013R* for a discussion).

Conclusion

As the National Research Council (1) report emphasizes, natural and social scientists need to develop the research base for climate science and economics substantially to refine our estimates of the SCC. Over the last decade, federal regulations with estimated benefits of over $1 trillion have used the SCC. Although damages, particularly those in poor regions, have proven most difficult to develop firm estimates for, revisions in the SCC estimates involve many factors other than damages, including the carbon cycle and economic growth assumptions.

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Supporting Information

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Model Version

The base file for calculating the SCC is DICE2016R-091916s.gms. This is updated from the version of May 2016, with the primary change since the May version being the damage function. It runs for 500 y starting in 2015 over 5-y increments. The code is available on the website. The estimated SCC for 2015 in 2010 US international dollars is 31.20 per ton of CO_2. If set up in the General Algebraic Modeling System (GAMS) program, the results are in an output file named "Dice2016RResults.csv." Major changes are as documented in the manuscript. Other details are contained here. The models and discussion are available at www.econ.yale.edu/~nordhaus/homepage/DICEmodels09302016.htm.

Federal Regulations Using the SCC

The SCC has been used in many small and large federal regulations pertaining to the environment and energy. A recent compilation of costs and benefits as calculated in regulatory impact analyses is contained in ref. 15 and is also discussed in ref. 2. Important examples totaling over $500 billion in total benefits are ones relating to automobile fuel efficiency standards and power plants.

Growth-Corrected Discounting

Fig. 3 shows the importance of the growth-corrected discount rate in determining the SCC. This section describes that point further, drawing on ref. 2. Assume that we linearize all of the equations of the DICE model and that all environmental variables have reached a stationary state where emissions, concentrations, population, temperature, and other physical variables are constant. Output, consumption, and damages are growing at constant rate g, and the goods discount rate is r. If we perturb emissions by 1 unit, this will cause a path of damages that is distributed over the distant future. For simplicity, assume that the damages start immediately but the damage–output ratio declines at a decay rate of δ per year.

We can use the Ramsey equation to evaluate the SCC as a function of the key variables. The Ramsey equation provides the equilibrium rate of return in an optimal growth model with constant growth in population and per capita consumption without risk or taxes. In this equilibrium, the real interest rate (r) equals the pure rate of social time preference (ρ) plus the rate of growth of per capita consumption (g) times the consumption elasticity of the utility function (α). In long-run equilibrium, we have the Ramsey equation $r = \rho + \alpha g$. The key variable will be the growth-corrected discount rate, $r - g$. Under our assumptions, $r - g = \rho + (\alpha - 1)g$. To simplify, assume that $\alpha = 1$, or that the utility function is logarithmic, which implies that $r - g = \rho$. [These long-run growth and discounting assumptions are used in *The Stern Review* (10) and are approximately the case for the DICE model.] Under these assumptions, the SCC is proportional to $1/(\rho + \delta)$. This relationship is shown by the near-hyperbolic curve in Fig. 3.

Damage Function Revision

The major change in DICE-2016R is the method for estimating the damage function. In earlier versions until 2010, we relied on either estimates gathered by the team at Yale or by surveys. The 2013 version relied on the Tol survey of damages (6, 7). This survey contained numerous errors and could not be used in the present version. The basic method for setting the damage function was similar to that in the DICE-2013R model as described in ref. 3. The method for calculating the damage function is described here.

We examined different damage estimates and used these as underlying data points and then fitted a regression to the data points. We also added an adjustment of 25% for omitted sectors and nonmarket and catastrophic damages, as explained in ref. 3.

The new estimates start with the survey of damage estimates by the author and Andrew Moffat. The survey included 26 studies. Of these, 16 contained independent damage estimates and were included, and, of these, 9 received full weight. Those receiving less than full weight were ones that were earlier (but different) versions of a model (for example, the FUND model) or had serious shortcomings. If a study had several estimates (say, along a damage function), the sum of the weights was constrained to be 1.

The estimates were made using four techniques. The central specification was a one-parameter quadratic equation with a zero intercept and no linear term. Unweighted least squares and median regressions generally had lower coefficients than the weighted versions. The weighted ordinary least squares (OLS) estimates had slightly higher coefficients than the weighted median regression. Additionally, the tests were made with different lower bound thresholds from 0 °C to 4 °C, and upper bound estimates from 3 °C to 10 °C, but these made virtually no difference to the estimates. A specification with both linear and quadratic terms was extremely unstable and was rejected.

The final estimate was an equation with a parameter of −0.236% loss in global income per degree Celsius squared; this leads to a damage of 2.1% of income at 3 °C, and 8.5% of global income at a global temperature rise of 6 °C. This coefficient is slightly smaller than the parameter in the DICE-2013R model (which was −0.267% per degree Celsius squared). The change from the earlier estimate is due to corrections in the estimates from the Tol numbers, inclusion of several studies that had been omitted from that study, greater care in the selection of studies to be included, and the use of weighted regressions.

The uncertainty of the damage coefficient is an ingredient in the uncertainty analysis discussed in *Uncertainty Estimates*. From a technical standpoint, the t statistic on the estimated coefficient is −7.8, so it is extremely well determined. However, this estimate does not reflect specification uncertainty, parameter uncertainty, or study dependence. As an illustration, the prediction of the different specifications at 3 °C is 3.8 times the SD for the one-parameter specification and 2.2 times the SD for the two-parameter specification. We have taken a polar value for the uncertainty of the damage parameter that is one-half the parameter. This value reflects the great divergence today among different studies.

Decomposition of the Change in SCC

Calculating the decomposition of the SCC by major change is straightforward. It involves introducing parametric changes in a cumulative fashion. For example, the change in "Economics" involves using the earlier value of world GDP and productivity growth instead of the 2016 version.

Regional Estimates of SCC

The regional estimates of the SCC are drawn from ref. 2 for the three IAMs. The discounted value of GDP for different regions is constructed as follows: We took estimates of 2020 GDP for countries and regions from the IMF World Economic Outlook database for April 2016.

Uncertainty Estimates

To estimate the uncertainty of the SCC, we discretized the distributions of three key uncertain variables and estimated the SCC for each discrete combination. More precisely, the probability density functions (pdfs) for the variables were taken from the MUP (5) study for ETS and productivity growth and from the damage survey for the damage coefficient. The means and SDs of the variables were (0.236, 0.118)% of income per degree Celsius squared for the damage parameter, (3.10, 0.84) °C for equilibrium CO_2 doubling for the ETS, and (1.52, 1.00)% per year for initial-period productivity growth.

The pdfs for each of the three uncertain variables were divided into deciles, and the mean of each decile was calculated for each uncertain variable. The mean for each variable across its deciles was therefore the mean of the variable; this produces 1,000 equally probable states of the world, and runs were made for each state of the world with no policy. In terms of decision theory, these are an "act, then learn" set of outcomes. The SD of the SCC for 2015 was $31.5 per ton of CO_2.