# Developing a Social Cost of Carbon for US Regulatory Analysis: A Methodology and Interpretation

Michael Greenstone*, Elizabeth Kopits†, and Ann Wolverton†

## Introduction

A few years ago, it seemed possible, perhaps even likely, that the United States and other major emitters of greenhouse gases (GHGs) would confront climate change by adopting a coordinated set of policies including the possibility of linked cap-and-trade systems. However, given the failure of the United States to enact a domestic cap-and-trade system and the nonbinding commitments of the 2009 Copenhagen Accord,[1] a global, coordinated solution to climate change appears to be out of reach for at least the next several years. Instead, the United States and many other countries are likely to pursue their own, more targeted policies to reduce GHG emissions, ranging from subsidies for the installation of low-carbon energy sources to regulations requiring energy efficiency standards in buildings, motor vehicles, and even vending machines to rebates for home insulation materials. Individually, these policies are expected to have only a marginal impact on atmospheric concentrations of GHGs (Bianco and Litz 2010).

Faced with numerous policy options to reduce GHG emissions, how is a government to identify those that are the most worthwhile? The key is to determine the monetized damages associated with an incremental increase in carbon emissions, generally referred to as the social cost of carbon (SCC).[2] The SCC is intended to include (but is not limited to) changes in net

*Massachusetts Institute of Technology and National Bureau of Economic Research, Cambridge, MA; e-mail: mgreenst@mit.edu.

†U.S. Environmental Protection Agency, Washington, DC; e-mail: kopits.elizabeth@epa.gov, wolverton.ann@epa.gov.

The authors thank Charlie Kolstad, Robert Kopp, Alex Martin, Steve Newbold, Robert Stavins, Cass Sunstein, and two anonymous referees for insightful comments. The views expressed in this article are those of the authors and do not necessarily represent those of the US Environmental Protection Agency or the Massachusetts Institute of Technology. All three authors worked for the Council of Economic Advisers in 2009 and/or 2010 and actively participated in the process to develop a social cost of carbon for the United States.

[1]The Copenhagen Accord is the outcome of the 2009 Copenhagen Climate Change Summit, at which more than two dozen key countries, accounting for more than 80 percent of the world's GHG emissions, agreed to reduce their emissions and to register their national commitments by the end of January 2010.

[2]It is important to note that the SCC described in this article is not intended to be used to estimate the benefits of policies such as coordinated global agreements that are expected to produce nonmarginal reductions in GHG emissions.

*Review of Environmental Economics and Policy*, volume 7, issue 1, winter 2013, pp. 23–46
doi:10.1093/reep/res015

Published by Oxford University Press on behalf of the Association of Environmental and Resource Economists 2013.

agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services. Monetized estimates of the economic damages associated with carbon dioxide ($CO_2$) emissions make it possible for benefit–cost analyses to incorporate the social benefits of regulatory actions that are expected to reduce these emissions. As the US Environmental Protection Agency (EPA) begins to regulate GHGs under the Clean Air Act and other agencies promulgate regulations aimed at reducing energy consumption, the SCC can help to identify regulations that have positive net benefits.

With these objectives in mind, the US government established an interagency working group, composed of scientific and economic experts from the White House as well as the EPA, the Departments of Agriculture, Commerce, Energy, and Transportation, and the Treasury Department, to develop a transparent and economically rigorous way to value the reductions in $CO_2$ emissions that result from federal regulations.[3] Between 2009 and 2010, the working group developed four estimates of the global damages per ton of $CO_2$ emissions, which have been used in regulatory impact analyses since their release (Interagency Working Group on Social Cost of Carbon 2010). The process that developed these SCC values was the first US government effort to consistently calculate the social benefits of reducing $CO_2$ emissions for use in the benefit–cost analysis of potential federal regulations. Previously, reductions in $CO_2$ emissions were either not valued or the values that were employed varied substantially across agencies.

The interagency group developed the range of SCC values using three well-known integrated assessment models (IAMs), a range of socioeconomic and emissions scenarios, three discount rates, and a probability distribution for equilibrium climate sensitivity (ECS). For emission changes occurring in 2010, the central SCC value is \$21 per ton of $CO_2$ emissions, with sensitivity analyses to be conducted at \$5, \$35, and \$65 (all values are in 2007 dollars per ton of $CO_2$). These SCC estimates grow over time based on rates endogenously determined within each model. For instance, the central value increases to \$26 per ton of $CO_2$ in 2020.

This article summarizes the methodology used by the interagency working group to develop a range of SCC estimates for use in regulatory decision making (in many instances, borrowing language directly from the interagency report), discusses how these SCC estimates can be used to inform regulatory decisions, and identifies priorities for future research.[4] We note at the outset that developing estimates of the SCC requires making many assumptions, and it is inevitable that some readers will not agree with all of them. Our aim here is to describe these assumptions in sufficient detail to enable readers to conduct their own research and suggest improvements so that future efforts to revise the SCC will rely on a methodology that improves on the one described here.

The article is organized as follows. The next section describes the three IAMs used to estimate the SCC. This is followed by a discussion of the main modeling assumptions made by the interagency group. Next we describe how the interagency group calculated and then selected the SCC values. The following section summarizes the main limitations of IAMs and identifies priorities for future research. Conclusions are presented in the final section.

[3]The goal was to develop a range of SCC values that use a defensible set of input assumptions, are grounded in the existing literature, and reflect key uncertainties and model differences.
[4]The interagency report is available in full at http://www.whitehouse.gov/sites/default/files/omb/inforeg/for-agencies/Social-Cost-of-Carbon-for-RIA.pdf (accessed November 19, 2012).

## IAMs and Their Damage Functions

Analysts face a number of challenges when attempting to estimate the economic consequences of $CO_2$ emissions. In particular, it is necessary to make assumptions concerning the four main steps in the estimation process: (1) the future emissions of GHGs, (2) the effects of past and future emissions on the climate system, (3) the impact of changes in climate on the physical and biological environment, and (4) the translation of these environmental impacts into economic damages. Researchers have developed IAMs to combine these steps into a single modeling framework; the word *integrated* reflects the fact that these models combine insights drawn from both science and economics. However, the advantages of using a single integrated framework are gained at the expense of a more detailed representation of the underlying climatic and economic systems.

The interagency group relied on three IAMs commonly used to estimate the SCC: the Dynamic Integrated Climate and Economy (DICE), the Policy Analysis of the Greenhouse Effect (PAGE), and the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) models.[5] Each of the three models is given equal weight in the SCC values developed by the interagency group. A number of simplifying assumptions and judgments underlie the three IAMs, reflecting the modelers' best attempts to synthesize the available scientific and economic research. Although the frameworks of other IAMs may better reflect the complexity of the science, they do not link physical impacts to economic damages, an essential step for estimating the SCC.

DICE, PAGE, and FUND all take highly simplified (i.e., reduced-form) approaches to estimate the SCC (see National Resource Council [NRC] 2009; Nordhaus 2008). They translate emissions into changes in atmospheric GHG concentrations, atmospheric concentrations into changes in temperature, and changes in temperature into economic damages. The baseline emissions projections are based on specified socioeconomic (gross domestic product [GDP] and population) pathways. These emissions are translated into concentrations using the carbon cycle built into each model, and concentrations are translated into changes in temperature based on each model's simple representation of the climate and a key parameter, climate sensitivity. Finally, the effects of temperature change are monetized based on one or more functions that translate the physical impacts associated with temperature increase into economic damages and the discount rate that is used to convert the stream of economic damages over time into a single value.

### Mapping Changes in Temperature to Changes in Economic Damages

Each model takes a somewhat different approach to modeling how changes in temperature are manifested as economic damages. In PAGE, damages are divided into three broad

[5]These models are frequently cited in the peer-reviewed literature and are used in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2007). The DICE model was developed by William Nordhaus in 1990 (Nordhaus 2008; Nordhaus and Boyer 2000). The PAGE model was developed by Chris Hope in 1991 for use by European decision makers (Hope 2006, 2008) and underlies *The Stern Review* (Stern 2007). The FUND model was developed by Richard Tol in the early 1990s (e.g., Anthoff et al. 2009; Tol 2002a, 2002b, 2009). The interagency group did not use the World Induced Technical Change Hybrid model (Bosetti, Massetti, and Tavoni 2007), which is occasionally cited in the literature, although generally less frequently than DICE, PAGE, and FUND.

categories: economic, noneconomic, and catastrophic. The consumption-equivalent damages in each period are calculated as a fraction of GDP, depending on the temperature in that period relative to the preindustrial average temperature in each region. In FUND, damages in each period also depend on the rate of temperature change from the previous period. Notably, this model estimates the damages separately for eight different market and nonmarket sectors: agriculture, forestry, water, energy, sea level rise, ecosystems, human health, and extreme weather. In DICE, temperature affects both consumption and investment. Although the model is calibrated to include the effects of temperature changes on the production of market and nonmarket goods and services, these impacts are not estimated separately in the model. However, DICE does incorporate impacts on agriculture, coastal areas (due to sea level rise), energy use, human health, nonmarket amenities (based on outdoor recreation), and human settlements and ecosystems. Unlike the approach in FUND and PAGE, in DICE GDP is endogenous, which means that damages experienced in one year reduce GDP in future years.[6]

The PAGE and DICE damage functions also explicitly include the possibility of catastrophes at higher temperatures. PAGE models catastrophes probabilistically as a function of a threshold temperature, the rate at which the likelihood of a catastrophe increases above the threshold, and the magnitude of the resulting catastrophe. DICE includes the expected value of damages associated with low-probability, high-impact "catastrophic" climate change. FUND does not explicitly include catastrophic damages.

Moreover, as we will discuss next, in estimating the SCC the interagency group chose to treat climate sensitivity (i.e., the temperature change associated with a given change in atmospheric concentrations of $CO_2$) probabilistically, which preserves the influence of nonlinearities in the damage functions.

## Accounting for Adaptation

The three models vary widely in how they account for compensatory adjustments, or adaptation, in response to climate change, which will mitigate the negative impacts on well-being. FUND allows for induced adaptation in certain sectors. PAGE assumes adaptation reduces climate impacts, but it is imposed exogenously. For instance, PAGE assumes that developed countries can eliminate up to 90 percent of all economic impacts beyond a 2°C increase and developing countries can eventually eliminate 50 percent of economic impacts. DICE does not account for adaptation explicitly, although it is included implicitly through the choice of studies used to calibrate the damage function. It is possible that the three models fail to account adequately for the various ways in which adaptation could occur. However, the evidence available on this issue is limited. Thus the interagency group retained the modelers' assumptions in this regard.

## Damage Functions

Figure 1 presents the damage functions for each IAM, based on the modeler's default scenarios and assumptions. The x-axis indicates increases in annual temperature in 2100; the y-axis

[6]Since DICE allocates economic output net of climate damages to consumption and investment, reduced damages in early periods due to mitigation action by other countries can lead to increased economic output (and hence increased absolute damages) in later periods.

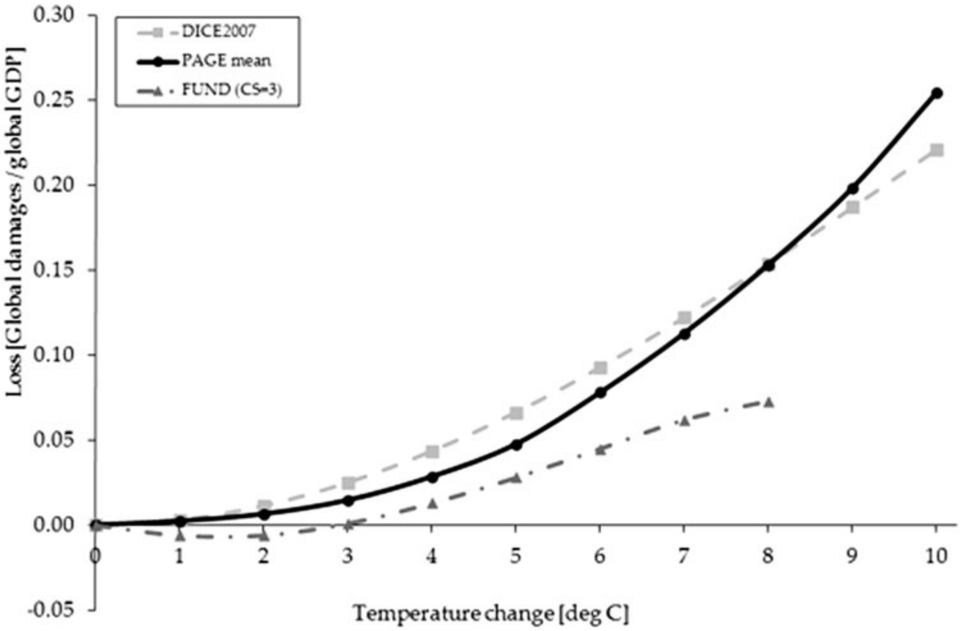


**Figure 1** Projected annual consumption loss as a fraction of global GDP in 2100 due to an increase in annual global temperature: DICE, FUND, and PAGE models
*Notes:* These damage functions reflect the default assumptions in each model; they reflect neither those interagency assumptions that differ from the default values nor the probabilistic treatment of parameters.
*Source:* Figure 1A, Interagency report.

indicates the annual consumption loss in 2100 as a share of global GDP. There are significant differences between models at both lower and higher increases in global-average temperature, reflecting, in part, differences in assumptions about the rate of technological change and the ability of human and natural systems to adapt to the effects of climate change.[7] The FUND damage function predicts that temperature increases up to about 3°C are beneficial due to the combined effect of $CO_2$ fertilization in the agricultural sector, positive impacts of higher temperature on some regions, and increases in temperature that are sufficiently slow to allow for adaptation (thus resulting in lower damages).

## The Power and Limitations of IAMS

Overall, the power of IAMs is that they offer some guidance concerning the complex issue of how an additional ton of GHGs will affect human well-being. Estimating these impacts is no small task, and this is what makes these models so attractive to researchers. However, the results are highly dependent on assumptions (e.g., the rate of economic growth in different countries, when certain technologies will come online, how quickly societies can adapt to climate impacts) that cannot be easily verified. Indeed, the differences across the damage functions, as indicated

[7]Although not reflected in Figure 1, it is worth noting that the models vary in what is treated probabilistically. In DICE, parameters are handled deterministically and represented by fixed constants. In contrast, in PAGE and FUND, most parameters are represented by probability distributions.

by Figure 1, underscore the need for continued research aimed at improving how the models incorporate adaptation, technological change, and catastrophic damages.[8]

# KEY MODELING ASSUMPTIONS

A key objective of the interagency process was to develop a methodology for exploring and assessing the SCC using each of the three IAMs in a way that was consistent and comparable while respecting the modelers' different approaches to quantifying damages. With this in mind, the interagency group conducted an extensive review of the literature and identified three key input parameters—socioeconomic and emissions trajectories, climate sensitivity, and discount rates—that were made consistent across the three models. All other model features were left unchanged, thus relying on the modelers' best estimates and judgments. This section discusses the assumptions made by the interagency group concerning these three key parameters as well as the group's decisions about how to address other important modeling issues.

## Socioeconomic and Emissions Trajectories

Socioeconomic pathways are closely tied to climate damages because, all else equal, more and wealthier people tend to emit more GHGs and also have a higher (absolute) willingness to pay to avoid climate disruptions. For this reason, it is standard to model several variables in tandem: GDP, population, $CO_2$ emissions, and the warming impact of non-$CO_2$ GHGs. To determine which scenarios to use as inputs in the analysis, the interagency group examined a plausible range of outcomes for these variables, with the aim of developing estimates of the damages associated with the marginal changes in emissions from these scenarios.

### The Stanford Energy Modeling Forum scenarios

To derive the socioeconomic and emissions pathways in a transparent manner, the interagency group relied on the results of the Stanford Energy Modeling Forum exercise, EMF-22.[9] A key advantage of relying on these data is that the GDP, population, and emission trajectories are internally consistent for each scenario evaluated. However, a key disadvantage is that these data allowed for only a crude probabilistic accounting of the likelihood of future mitigation action by other countries.

Five trajectories were selected from EMF-22 to represent the socioeconomic and emissions pathways (see Table 1), and all of the trajectories were given equal weight in the interagency group's derivation of the SCC. The first four trajectories represent business-as-usual (BAU) growth in population, wealth, and emissions and are associated with $CO_2$ (only) concentrations ranging from 612 to 889 parts per million (ppm) in 2100 (although none of these four scenarios reaches stabilization by 2100).[10] The fifth trajectory represents an emissions pathway that

[8]Later we discuss in more detail the models' limitations in accounting for various scientific and economic processes.

[9]The Energy Modeling Forum (EMF) is an international forum for sharing and facilitating discussions on energy policy and global climate issues among experts. Participating institutions from around the world are periodically brought together to examine a single topic to which many existing models can be applied. EMF-22 included analysis from 10 models of international climate change control scenarios.

[10]The 2100 concentrations are 889 ppm for MERGE Optimistic, 612 ppm for MESSAGE, and 794 ppm for MiniCAM. The IMAGE 2100 concentration is not provided in the EMF data file.

**Table 1** Global socioeconomic and emissions projections from five EMF-22 reference scenarios

| | | | | Annualized % change | |
|---|---|---|---|---|---|
| **EMF-22–based scenarios** | **2000** | **2050** | **2100** | **2000–2050** | **2050–2100** |
| **A.** Fossil and industrial $CO_2$ emissions ($GtCO_2$/year) | | | | | |
| IMAGE | 26.6 | 45.3 | 60.1 | 1.1 | 0.6 |
| MERGE Optimistic | 24.6 | 66.5 | 117.9 | 2.0 | 1.2 |
| MESSAGE | 26.8 | 43.5 | 42.7 | 1.0 | 0.0 |
| MiniCAM | 26.5 | 57.8 | 80.5 | 1.6 | 0.7 |
| 550 ppm average* | 26.2 | 20.0 | 12.8 | −0.5 | −0.9 |
| **B.** GDP per capita (using market exchange rates, 2005$) | | | | | |
| IMAGE | 6,328 | 17,367 | 43,582 | 2.0 | 1.9 |
| MERGE Optimistic | 6,050 | 13,633 | 27,629 | 1.6 | 1.4 |
| MESSAGE | 6,246 | 16,351 | 32,202 | 1.9 | 1.4 |
| MiniCAM | 6,017 | 14,284 | 42,471 | 1.7 | 2.2 |
| 550 ppm average | 6,082 | 15,793 | 37,132 | 1.9 | 1.7 |
| **C.** Global population (billions) | | | | | |
| IMAGE | 6.1 | 9.0 | 9.1 | 0.8 | 0.0 |
| MERGE Optimistic | 6.0 | 9.0 | 9.7 | 0.8 | 0.1 |
| MESSAGE | 6.1 | 9.4 | 10.4 | 0.9 | 0.2 |
| MiniCAM | 6.0 | 8.8 | 8.7 | 0.8 | 0.0 |
| 550 ppm average | 6.1 | 8.7 | 9.1 | 0.7 | 0.1 |

*Notes:* The models were calibrated from a 2000 base year.
* In the fifth scenario, 2000–2100 projections are equal to the average of the 550 ppm CO2e stabilization scenarios considered by each of the four models used to represent the BAU trajectories (IMAGE, MERGE Optimistic, MESSAGE, and MiniCAM).
*Source:* The socioeconomic scenarios are available at Stanford's Energy Modeling Forum: http://emf.stanford.edu/events/emf_briefing_on_climate_policy_scenarios_us_domestic_and_international_policy_architectures/ (accessed November 19, 2012).

achieves stabilization at 550 ppm $CO_2e$ (i.e., $CO_2$-only concentrations of 425 to 484 ppm) in 2100 due to widespread mitigation by countries around the world. Since each socioeconomic pathway is given equal weight, this scenario is assigned a 20 percent chance of occurring.

## Caveats

A few caveats are in order. First, the EMF-22 BAU scenarios represent the modelers' judgment of a likely emissions pathway rather than the wider range of possible outcomes that could occur. Nevertheless, these views range from the more optimistic (e.g., abundant low-cost, low-carbon energy) to more pessimistic (e.g., constraints on the availability of nuclear and renewables). It is also worth noting that the emissions trajectories underlying some BAU scenarios (e.g., MESSAGE) are consistent with modest policy action to address climate change.

Second, the 550 ppm socioeconomic trajectory is not derived from an assessment of what policy is optimal from a benefit–cost standpoint. Rather it represents the potential for aggressive mitigation efforts in the future. The interagency group chose not to include socioeconomic trajectories that achieve GHG concentrations lower than 550 ppm because many of the models that are included in the EMF-22 could not meet this target (i.e., they had difficulty converging).

Third, the approach used by the interagency group to specify the baseline scenarios does not account for some potentially important future scientific, economic, and policy changes and their dynamic influence on the models. For example, new evidence that leads scientists to revise the climate sensitivity or expected global temperature response to GHG accumulation in the atmosphere would require a change in the temperature forecasts in these IAMs. This new evidence might also lead to policy actions that either reduce or increase the stringency of GHG regulations, which would require a change in the emissions and temperature forecasts. Other forms of learning and policy responses could also change the SCC in the long run. Thus it is important that the SCC values be reestimated over time using updated assumptions about socioeconomic and emissions trajectories that reflect new information and new measures to reduce emissions.

## Equilibrium Climate Sensitivity

ECS is a key input parameter in DICE, PAGE, and FUND. It determines the speed and magnitude of temperature change for a given emissions path and is defined as the increase in the annual global-average surface temperature from a doubling of atmospheric $CO_2$ concentration, relative to preindustrial levels (or stabilization at a concentration of approximately 550 ppm). ECS reflects a relatively short- to medium-term response (100 to 200 years) because it does not include long-term feedback effects due to possible large-scale changes in ice sheets or the biosphere that occur on a time scale of many hundreds to thousands of years (e.g., Hansen et al. 2007).

### Uncertainties concerning climate sensitivity

Uncertainties concerning this important parameter have received substantial attention in the peer-reviewed literature (see, e.g., Roe and Baker 2007). However, the most authoritative statement about ECS appears in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC):

> Basing our assessment on a combination of several independent lines of evidence . . . including observed climate change and the strength of known feedbacks simulated in [global climate models], we conclude that the global mean equilibrium warming for doubling $CO_2$, or "equilibrium climate sensitivity," is likely to lie in the range 2°C to 4.5°C, with a most likely value of about 3°C. Equilibrium climate sensitivity is very likely larger than 1.5°C.
>
> For fundamental physical reasons as well as data limitations, values substantially higher than 4.5°C still cannot be excluded, but agreement with observations and proxy data is generally worse for those high values than for values in the 2°C to 4.5°C range. (Meehl et al. 2007, 799)

### Selection of ECS distribution

After consulting with several lead authors of the IPCC report, the interagency group considered four possible probability distributions to represent ECS.[11] In each case, the distribution was

[11]The four candidate probability distributions considered were Roe and Baker (2007), log-normal, gamma, and Weibull. Log-normal, gamma, and Weibull distributions are often used to characterize skewed nonnegative data.

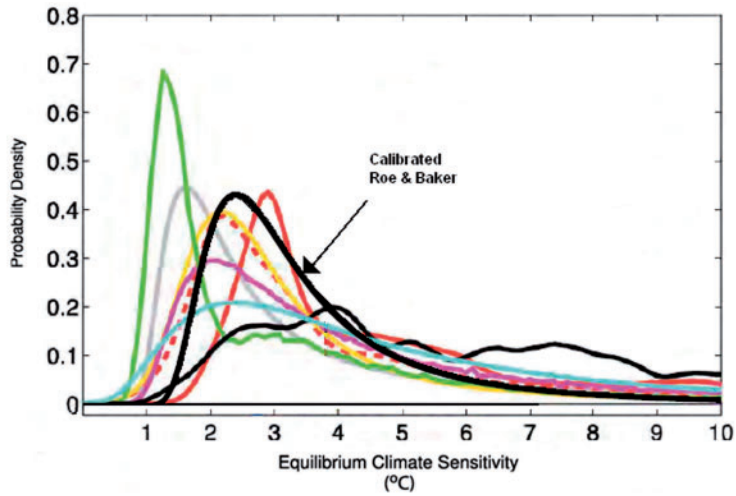


**Figure 2** Comparison of estimates of the probability density function for ECS (°C)
*Notes:* The calibrated Roe and Baker distribution has been included for comparison purposes.
*Source:* Adapted from *Climate Change 2007: The Physical Science Basis*. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure 9.20. Cambridge and New York: Cambridge University Press.

calibrated by applying three constraints from the IPCC's Fourth Assessment Report: (1) a median equal to 3°C; (2) two-thirds probability that the ECS lies between 2 and 4.5°C; and (3) zero probability that it is less than 0°C or greater than 10°C (see Hegerl et al. 2006, 721).

The interagency group chose the calibrated Roe and Baker (2007) distribution from among the four candidates for two reasons. First, the Roe and Baker distribution is the only distribution based on a theoretical understanding of the response of the climate system to increased GHG concentrations (Roe 2008; Roe and Baker 2007). Second, of the distributions considered, it best reflects the IPCC judgment that "values substantially higher than 4.5°C still cannot be excluded." It is also worth noting that while the Roe and Baker distribution puts a somewhat higher probability on the likelihood that the ECS "is very likely larger than 1.5°C" (quoting from IPCC 2007), it is not inconsistent with the IPCC's statement.

Figure 2 illustrates how the calibrated Roe and Baker distribution compares to estimates of the probability distribution function of ECS in the empirical literature. More specifically, it overlays the calibrated Roe and Baker distribution on distributions estimated by the studies used to support the IPCC statement about likely values for ECS.[12]

## Discount Rates

The discount rate is intended to reflect society's marginal rate of substitution between consumption in different time periods. To evaluate proposed US government regulations that have both intra- and intergenerational effects, government agencies have traditionally used constant discount rates of 3 and 7 percent in their benefit–cost analyses (Office of Management and Budget [OMB] 2003). However, the choice of a discount rate to be used over very long periods of time raises highly contested and exceedingly challenging scientific,

[12]The functions are scaled to integrate to unity between 0°C and 10°C.

economic, philosophical, and legal issues. As a result, there is no widespread agreement in the literature concerning the discount rates that should be used in an intergenerational context.[13]

Not surprisingly, discounting plays a critical role in determining the SCC estimates. To see this, note that the SCC is calculated by estimating the damages from an additional unit of $CO_2$ emitted in a particular year in terms of reduced consumption due to the impacts of elevated temperatures in the future. Because $CO_2$ has a half-life of approximately a hundred years, the damages from a unit of emissions occur over many decades. The discount rate is used to calculate the present value of the stream of damages in the year when the additional unit of emissions was released.

Arrow et al. (1996) outlined both descriptive and prescriptive approaches for determining the discount rate for climate change analysis. The descriptive approach reflects a positive perspective based on observations of people's actual choices (e.g., savings versus consumption decisions over time, allocations of savings among more and less risky investments). Advocates of this approach generally suggest inferring the discount rate from market rates of return since expenditures made today to mitigate GHG emissions are financed out of current consumption like any other investment. In contrast, the prescriptive approach reflects the normative judgments of the decision maker (e.g., how interpersonal comparisons of utility should be made and how the welfare of future generations should be weighed against that of the present generation). Many advocates of this approach tend to argue for relatively low discount rates (e.g., Stern 2007). In the discussion that follows, we briefly outline the main factors that the interagency group considered when choosing particular discount rates.

### Using historically observed interest rates

Although the interagency group found some appeal to relying on historically observed interest rates for discounting climate damages, in a world with heterogeneous returns to equities, gold, corporate bonds, and Treasury bills, which is the correct interest rate to use? The return on an investment made today in climate mitigation is reflected in the higher level of consumption available in the future due to reduced changes in climate (i.e., smaller temperature increases). This suggests that climate mitigation should be compared with standard public investments that increase the well-being of future generations; in fact, future generations would want the current generation to make investment choices in this manner.

Thus the critical issue is how the returns to climate mitigation are correlated with the uncertain returns to investments in the overall economy, which are frequently proxied by overall equity returns.[14] In this context, we need to consider three cases. The first case occurs when the returns to climate mitigation are perfectly correlated with the economy's overall growth rate, which would be the case if climate change damages are a fixed share of GDP. In this case, the proper discount rate is the expected return on investments in the economy as a

[13]For a detailed discussion of the factors the interagency group considered when selecting discount rates for the SCC, see the full interagency report. Portney and Weyant (1999) and Heal (2009) also discuss the challenges of intergenerational discounting.

[14]The correlation between these climate mitigation investments and overall economy-wide growth can be viewed as the beta in the capital asset pricing model, which measures how changes in market returns affect an individual investment's returns. Becker, Murphy, and Topel (2010) and Weitzman (2007) provide insightful discussions of these issues.

whole. The second case occurs when the returns to climate mitigation investments are uncorrelated with the economy's overall growth rate. Here, the appropriate discount rate is the riskless interest rate. The third case occurs when the returns to climate mitigation are negatively correlated with the economy's growth rate. For example, a climate mitigation project may generate positive returns when the overall economy is doing poorly and the marginal utility of an additional unit of consumption is especially high. In other words, these investments may have a low expected return but pay off when they are most valuable. In this case, it would be appropriate to use discount rates that are smaller than the riskless rate. Thus the appropriate discount rate depends on an assumption about how the returns to climate mitigation investments correlate with the overall economy. However, there is no consensus on this issue in the literature.

### The Ramsey equation

The interagency group also found the representative agent discounting framework developed by Ramsey (1928) to be useful in its discussion of what discount rate to use for evaluating damages over long time frames. This approach leads, under certain assumptions, to the Ramsey discounting formula, in which the interest rate at which future monetized damages are discounted equals the pure rate of time preference, $\delta$, plus the product of the growth rate of per capita consumption, g, and the elasticity of marginal utility of consumption, $\eta$. In other words, the social discount rate is equal to $\delta + \eta \times g$.[15] Under this approach, the analyst applies either positive or normative judgments in selecting values for the key parameters $\eta$ and $\delta$.

The literature generally adopts values for $\eta$ in the range of 0.5 to 3, with a clustering around 2 (Arrow 2007; Dasgupta 2007, 2008; Hall and Jones 2007; Nordhaus 2009; Szpiro 1986; Weitzman 2007, 2009). With respect to the pure rate of time preference, most articles in the climate change literature adopt values for $\delta$ in the range of 0 to 3 percent per year, and it is standard to assume rates of growth of consumption of around 2 percent in developed countries.[16] Researchers that rely on empirical observations to inform their selection of these parameters may use discount rates as high as 5 or 6 percent, while researchers informed by the prescriptive approach often choose parameters that imply discount rates between 1 and 3 percent.

### Uncertainty in the discount rate

Although the discount rate is an important driver of the benefits estimate, the interagency group also noted that it is uncertain over time. Weitzman (1998) showed theoretically and Newell and Pizer (2003) and Groom et al. (2007) confirmed empirically that discount rate uncertainty can have a large effect on net present values. A key result from these studies is that if the uncertainty in the discount rate is persistent (e.g., the rate follows a random walk[17]), then it

[15]See US EPA (2010a) for a general discussion of discounting concepts as they apply in an intergenerational context.

[16]The typically higher rates of growth in developing countries may help to explain their reluctance to make climate mitigation investments with payoffs that are several decades away (Deshpande and Greenstone 2010).

[17]This means that past behavior cannot be used to predict future behavior, which is why uncertainty cannot be resolved over time. There is no possibility of learning and improving one's predictions based on historical trends.

will result in a certainty-equivalent[18] discount rate that declines over time. Consequently, lower discount rates tend to dominate over the very long term (see Weitzman 1998, 1999). However, the issue of how to model discount rate uncertainty properly remains unresolved and continues to be an active area for research.

### The discount rates selected for estimating the SCC

Taking all of these factors into consideration, the interagency group ultimately chose three certainty-equivalent constant discount rates: 2.5 percent, 3 percent, and 5 percent per year. The two higher discount rates are principally informed by historically observed interest rates. The central value, 3 percent, is consistent with estimates in the economics literature as well as guidance from the OMB (2003) concerning the consumption rate of interest.[19] Moreover, 3 percent roughly corresponds to the after-tax riskless interest rate. The upper value of 5 percent is included to represent the possibility that climate damages are positively correlated with market returns. In addition, this discount rate may be justified by the high interest rates that many consumers use to smooth consumption across periods.[20]

The low value, 2.5 percent, is included to reflect the concern that interest rates are highly uncertain over time.[21] Furthermore, a rate below the riskless rate would be justified if climate investments were negatively correlated with the overall market rate of return. The use of the low (2.5 percent) value is also consistent with certain prescriptive judgments and ethical objections that have been raised about higher discount rates (see, e.g., Heal 2009; Stern 2008; Stern 2007; Sterner and Persson 2008).

## Global versus Domestic SCC

Another important issue in estimating the SCC was whether to include damages that are projected to occur outside the United States. Current US government guidance (OMB 2003) requires that economically significant regulations be analyzed from the domestic perspective. [22]

[18]A certainty-equivalent value is calculated by determining the discount rate at which an individual would accept a certain or known result over a potentially higher, but uncertain, result.

[19]The consumption rate of interest is the rate one uses when current consumption mainly displaces future consumption, as opposed to also crowding out investment.

[20]To determine the posttax riskless rate, the interagency group calculated the average real return from Treasury notes over the longest time period available (from Newell and Pizer 2003) and adjusted for federal taxes (the average marginal rate from tax years 2003–6 is about 27 percent). This calculation produces a real interest rate of about 2.7 percent, roughly consistent with OMB Circular A-4's recommendation to use 3 percent to represent the consumption rate of interest. A measure of the posttax risky rate for investments whose returns are positively correlated with overall equity market returns can be obtained by adjusting pretax rates of household returns to risky investments (approximately 7 percent) for taxes, yielding a real rate of roughly 5 percent.

[21]This value represents the average of the certainty-equivalent rates from the random walk approach and the mean-reverting approach (in which over time, the discount rate tends to drift toward its long-term mean) used in Newell and Pizer (2003), starting at a discount rate of 3 percent. The calculations were done by William Pizer using the original simulation program from Newell and Pizer (2003).

[22]The development of a domestic SCC is greatly complicated by the relatively few region- or country-specific IAMs and even those that can produce a US-only SCC are incomplete because they do not account for how damages in other regions could affect the United States (e.g., global migration, economic and political destabilization). Using a 2.5 or 3 percent discount rate, the US benefit from reducing GHG emissions is, on average, about 7 to 10 percent of the global benefit across the scenarios analyzed with the FUND model. Viewing this issue in a different way, if the fraction of GDP lost due to climate change is assumed to be similar across countries, then the US benefit would be proportional to the US share of global GDP, which is currently about 23 percent. Note this value is highly speculative because there is no a priori reason why domestic benefits should be a constant fraction of net global damages over time.

However, analysis from the international perspective is optional. The interagency group concluded that a global measure of the benefits from reducing US emissions is preferable to a domestic measure because the climate change issue is highly unusual in at least two respects. First, it involves a global externality. That is, emissions of most GHGs contribute to damages around the world even if they are emitted in the United States. Consequently, to address the global nature of the problem, the interagency group concluded that the SCC should incorporate the full (global) damages caused by GHG emissions. Second, climate change is a problem that the United States cannot solve alone. Even if the United States were to reduce its GHG emissions to zero, it would be insufficient to avoid substantial damages from climate change.

### Utility Functions and Equity Weighting

Another modeling issue that needs to be addressed when quantifying the damages associated with a change in emissions is whether to employ "equity weighting" to aggregate changes in consumption across regions. Such weighting takes into account the relative reductions in wealth in different regions of the world (e.g., Anthoff et al. 2009). For instance, a per capita loss of $500 in GDP would be weighted more heavily for a country with a per capita GDP of $2,000 than for a country with a per capita GDP of $40,000. In standard economics terms, this would be consistent with a declining marginal utility of income.

Due to both practical and theoretical challenges, the interagency group concluded that this approach would not be appropriate for estimating a SCC value for use in domestic regulatory analysis. First, such equity weighting would require the development of a global utility function. Second, a full accounting of the effects of a policy would have to consider the cost side of the equation: that the given cost of an emissions reduction imposes a greater welfare loss on a poor nation than on a wealthy one.[23] Finally, explicitly using equity weighting in benefit–cost analysis, rather than conducting a separate distributional analysis, would be a departure from the US government's standard operating procedure.

## Calculating and Selecting SCC Values

To estimate SCC values for use in regulatory decision making, the interagency group ran each of the three IAM models (DICE, PAGE, and FUND) using the common set of assumptions described in the previous section:

- A Roe and Baker distribution (2007) for the climate sensitivity parameter, calibrated to IPCC statements;
- Five sets of GDP, population, and carbon emissions trajectories based on the selected EMF-22 scenarios; and
- Constant annual discount rates of 2.5 percent, 3 percent, and 5 percent.

[23]Indeed, the use of equity weighting to reflect global differences in costs and benefits would greatly complicate a global cap-and-trade regime for pollution permits.

## Basic Computational Steps

To ensure consistency across the three IAMs, climate damages were calculated as the lost consumption in each future year. The basic computational steps for calculating the SCC in a particular year *t* are:

(1) Enter the baseline path of emissions, GDP, and population,[24] and calculate the associated year-by-year paths of temperature and per capita consumption.
(2) Shock the models with additional carbon emissions in year *t* and recalculate the year-by-year paths of temperature and per capita consumption that result from the adjusted path of emissions in all years beyond *t*.
(3) Compute the marginal damages in each year as the difference between the per capita consumption estimated in step 1 and step 2.
(4) Discount the resulting path of marginal damages back to the year of emissions and calculate the SCC as a net present value.

These steps were repeated for each model out to 2050 to cover the time horizons anticipated for analysis of upcoming regulations. Because the climate sensitivity parameter is modeled probabilistically, and because PAGE and FUND incorporate uncertainty into other model parameters, the final output from each model run was a distribution of SCC values in year *t*. This exercise produced forty-five separate distributions of the SCC for a given year (i.e., the product of three models, three discount rates, and five socioeconomic scenarios), which is clearly too many separate distributions to inform decision making.

## Producing a Range of Plausible Estimates

To produce a range of plausible estimates that still reflects the uncertainty in the estimation process, the distributions from each of the models and scenarios were weighed equally and combined to produce three separate probability distributions for the SCC in a given year, one for each assumed discount rate. For example, Figure 3 presents the distribution of SCC values in 2010 that are associated with a 3 percent discount rate and based on 150,000 model runs. To sample the distribution of equilibrium climate sensitivities adequately, each of the fifteen model socioeconomic scenario pairs was run a total of ten thousand times, resulting in 5th, 25th, 50th, 75th, and 95th percentile SCC values of -$9, $4, $14, $28, and $65, respectively.

## Selecting Point Estimates for the SCC

Four point estimates were selected from these distributions to represent the global SCC in a given year. Because the literature indicates that the SCC is quite sensitive to assumptions about the discount rate, but there is no consensus on the appropriate rate to use in an

[24]To run each model through the year 2300 requires assumptions about GDP, population, GHG emissions, and radiative forcing trajectories after 2100, the last year for which these projections are available from the EMF-22 models. These inputs were extrapolated from 2100 to 2300 as follows: (1) population growth rate declines linearly, reaching zero in the year 2200; (2) GDP/per capita growth rate declines linearly, reaching zero in the year 2300; (3) the decline in the fossil and industrial carbon intensity ($CO_2$/GDP) growth rate over 2090–2100 is maintained from 2100 through 2300; (4) net land use $CO_2$ emissions decline linearly, reaching zero in the year 2200; and (5) non-$CO_2$ radiative forcing remains constant after 2100.

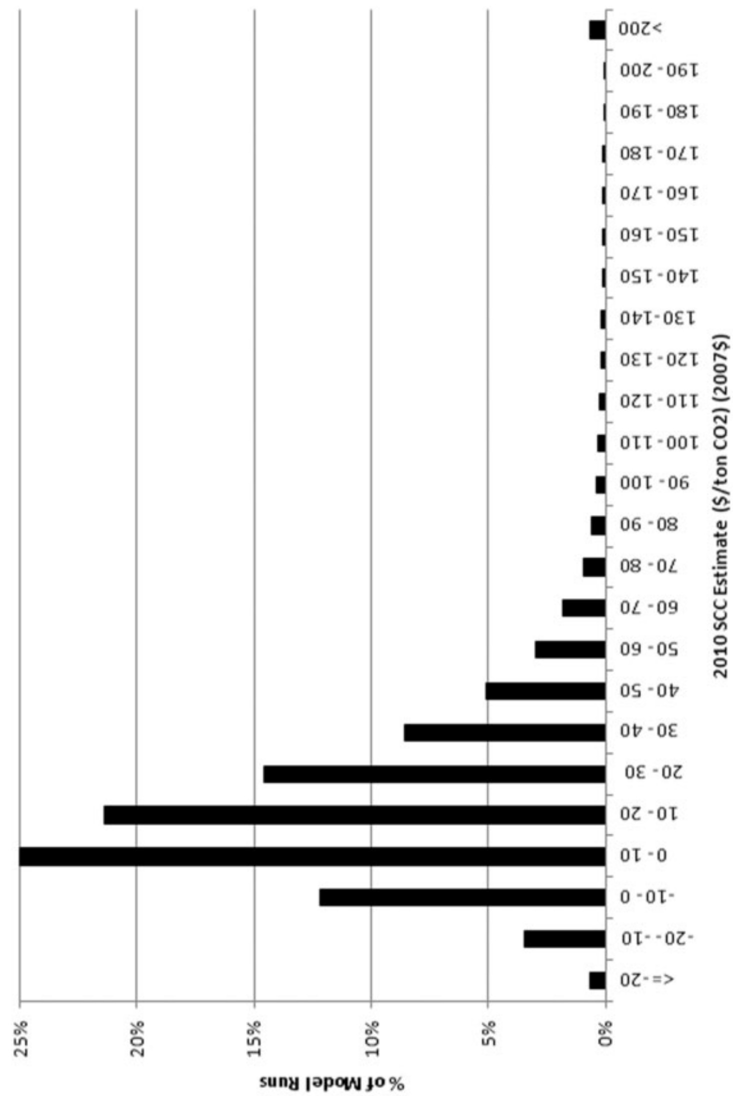


**Figure 3** Histogram of global SCC estimates in 2010 (2007$/ton $CO_2$), 3% discount rate
*Source*: DICE, PAGE, and FUND model runs used to generate interagency SCC values.

intergenerational context, the interagency group decided to calculate separate SCCs for each of the three discount rates. The central value is the average SCC across models and socioeconomic and emissions scenarios at the 3 percent discount rate. The second and third values are the average SCC at the 2.5 percent and 5 percent discount rates, respectively. The interagency group also chose to include a fourth value to represent the possibility of higher than expected economic impacts from climate change (i.e., those that are further out in the tails of the SCC distribution), such as the possibility that the climate system is more sensitive to a doubling of $CO_2$ than is represented by the models' damage functions at the mean climate sensitivity. Thus, for the fourth value, the group selected the SCC value for the 95th percentile at a 3 percent discount rate. For 2010, the central value of the SCC is $21 per ton of $CO_2$ emissions, with sensitivity analysis to be conducted at $5, $35, and $65. This last value is the SCC at the 95th percentile for a 3 percent discount rate.

## Variability of the SCC across Parameters and Models

Table 2 presents SCC estimates for 2010 by model, socioeconomic scenario, and discount rate and illustrates the variability in the SCC across the input parameters. The discount rate is the assumption that has the largest effect on the SCC, with higher discount rates resulting in lower SCC values for each socioeconomic trajectory. For example, the impact of the discount rate on FUND is especially evident in the 5 percent discount rate case where the mean SCC values are negative (i.e., there are benefits). Recall from Figure 1 that damages are negative in FUND for lower temperature increases. This means that because higher temperature increases do not occur until much further out in time, the discount rate effectively minimizes the influence of the years when there are damages relative to the years when there are benefits.

**Table 2** Social cost of $CO_2$ estimates for 2010 by model, socioeconomic trajectory, and discount rate (in 2007 dollars)

| | | Discount rate | | | |
|---|---|---|---|---|---|
| **Model** | **Socioeconomic reference scenario** | **5% Mean** | **3% Mean** | **2.5% Mean** | **3% 95th percentile** |
| DICE | IMAGE | 10.8 | 35.8 | 54.2 | 70.8 |
| | MERGE Optimistic | 7.5 | 22.0 | 31.6 | 42.1 |
| | Message | 9.8 | 29.8 | 43.5 | 58.6 |
| | MiniCAM | 8.6 | 28.8 | 44.4 | 57.9 |
| | 550 ppm average | 8.2 | 24.9 | 37.4 | 50.8 |
| PAGE | IMAGE | 8.3 | 39.5 | 65.5 | 142.4 |
| | MERGE Optimistic | 5.2 | 22.3 | 34.6 | 82.4 |
| | Message | 7.2 | 30.3 | 49.2 | 115.6 |
| | MiniCAM | 6.4 | 31.8 | 54.7 | 115.4 |
| | 550 ppm average | 5.5 | 25.4 | 42.9 | 104.7 |
| FUND | IMAGE | −1.3 | 8.2 | 19.3 | 39.7 |
| | MERGE Optimistic | −0.3 | 8.0 | 14.8 | 41.3 |
| | Message | −1.9 | 3.6 | 8.8 | 32.1 |
| | MiniCAM | −0.6 | 10.2 | 22.2 | 42.6 |
| | 550 ppm average | −2.7 | −0.2 | 3.0 | 19.4 |

*Source:* Table 3, Interagency report.

Table 2 also indicates that there are measurable differences in the estimated SCC across the three models. FUND produces the lowest estimates; PAGE generally produces the highest estimates. These results are qualitatively similar to the SCC values published in the literature, which are based on recent versions of each model (e.g., see Hope 2006, 2008; Nordhaus 2008).[25]

The socioeconomic scenarios have less impact on the SCC values than the other assumptions. Not surprisingly, when the model and discount rate are held constant, the SCC is generally the smallest with the 550 ppm scenario. This is because the marginal ton of emissions occurs over the range of temperatures for which the damage functions in Figure 1 are at relatively low levels. In FUND, this results in a small negative number at the 3 percent discount rate. This differs from the results in the other models at least in part because, in contrast to DICE and PAGE, in FUND, increases in income over time decrease vulnerability to climate change (a form of adaptation).

## Key Differences in Model Results

Finally, Table 2 indicates that the SCC values are smaller under the Model for Evaluating the Regional and Global Effects of GHG Reduction Policies (MERGE) optimistic scenario than under the 550 ppm scenario for PAGE and DICE, but this is not the case for FUND. This highlights a key difference in the models that is not evident when examining the results for the other scenarios. Notably, climate damages are represented in DICE and PAGE as the loss of a fraction of gross economic output in each period, which is a function of only the temperature anomaly in that period. In contrast, the climate damages in FUND depend on both the period's temperature anomaly and the rate of temperature change. The interaction between these two effects can result in a different rank ordering of scenarios with regard to incremental damages.

## SCC Values Beyond 2010

The SCC values for years beyond 2010 were calculated in the same way as the values for 2010, by combining all outputs (ten thousand estimates per model run) from all scenarios and models for a given discount rate in each year. The four estimates of the SCC for emissions in 2025 are on average $30 (using the 3 percent discount rate), $10 (using the 5 percent discount rate), $46 (using the 2.5 percent discount rate), and $90 for the 95th percentile (using the 3 percent discount rate). Using the 5 percent, 3 percent, and 2.5 percent discount rates, the SCC values increase at annualized rates of 3.1 percent, 1.9 percent, and 1.6 percent, respectively, over the 2010–50 period.[26] The SCC increases over time because future emissions are expected to produce larger incremental damages as physical and economic systems become more stressed in response to greater climatic change.

[25]However, those values are not based on the same set of assumptions that were used by the interagency group. In particular, discount rates were not assumed to be constant over the entire time horizon.

[26]See the interagency report for the four SCC values in five-year increments from 2010 to 2050.

## Limitations of Models and Priorities for Future Research

The SCC estimates presented here incorporate the latest research across the relevant scientific and economic literatures. However, during the course of the modeling, it became clear that several issues required additional exploration and research.[27] This section discusses four key areas where there are gaps or limitations in current knowledge and identifies priorities for future research. The discussion is aimed at encouraging the development of updated and improved methods for estimating the SCC for use in future benefit–cost analysis of government regulations.

### Incomplete Treatment of Noncatastrophic Impacts

The incremental (i.e., noncatastrophic or gradually occurring) impacts of climate change are expected to be widespread, diverse, and heterogeneous. However, the magnitude of these impacts is uncertain because of the inherent complexity of climate processes, and uncertainties concerning the economic behavior of current and future populations and the rate of technological change and adaptation. Although the IAMs used to estimate the SCC take a holistic approach, they cannot assign accurate values to all of the important physical, ecological, and economic impacts of climate change because precise information on the nature of damages is not always available, and even when it is, the models may lag behind the most recent research. Moreover, the models are calibrated over a relatively modest range of observed temperatures. Ocean acidification is one example of a potentially large but gradually occurring category of damages from $CO_2$ emissions that is not currently captured by the IAMs. Incremental species and wildlife loss is another example of economic damage that is exceedingly difficult to monetize. New research is clearly needed to quantify and monetize these types of impacts.

### Incomplete Treatment of Potential Catastrophic Impacts

There has been considerable discussion recently concerning the risk of catastrophic impacts of climate change and how best to account for extreme scenarios, such as large releases of methane from melting permafrost and warming oceans. The damage functions underlying the three IAMs used to estimate the SCC vary in the degree to which they capture the economic effects of such climate change–induced “catastrophes” (Mastrandrea 2009). In particular, the models’ functional forms may not adequately capture:

- potentially discontinuous “tipping point” behavior in the earth system;
- intersectoral and interregional interactions including global security impacts of higher levels of warming; and
- limited near-term potential for substitutability between damages to natural systems and increased consumption.

[27]For instance, a number of questions were raised regarding the form and inclusiveness of the economic damage function.

### Tipping points

The damage functions in the IAMs are typically calibrated by estimating damages at moderate temperature increases (e.g., DICE is calibrated at 2.5°C) and extrapolating to much larger temperature increases by assuming that damages increase as some power of the temperature change. However, recent science suggests that there are a number of potential climatic "tipping points" at which the earth system may exhibit discontinuous behavior with potentially severe social and economic consequences (e.g., Kriegler et al. 2009; Lenton et al. 2008).[28]

The implications of these tipping points have received increased attention in the economics literature. Weitzman (2009) suggests that catastrophic damages are extremely large—so large, in fact, that the damages from a low-probability catastrophic event far in the future dominate the effect of the discount rate in a present value calculation and result in an infinite willingness to pay for mitigation today. However, others conclude that the conditions under which Weitzman's results hold are limited (Newbold and Daigneault 2009; Nordhaus 2009; Pindyck 2012). Given this difference in opinion, further research is needed before its practical significance can be fully understood and a reasonable approach developed to account for such risks in regulatory analysis.

### Failure to incorporate intersectoral and interregional interactions

The damage functions underlying the three IAMs do not fully incorporate either intersectoral or interregional interactions. For instance, although most IAMs include damages to the agricultural sector, the effects of changes in the food supply on human health are not fully captured. Likewise, the effects of climate damages in one region on another region are not included in some models. Although difficult to quantify, these interregional interactions are the basis for climate-induced national and economic security concerns (e.g., Campbell et al., 2007; US Department of Defense 2010) and are more likely at higher levels of warming.

### Imperfect substitutability of environmental amenities

The IAMs assume it is possible to compensate for the economic consequences of damages to natural systems through increased consumption of nonclimate goods. Although this is a common assumption in many economic models, in the context of climate change, it is possible that the damages to natural systems could become so great that no increase in consumption of nonclimate goods would provide complete compensation, at least over the short or medium run (Levy, Babu, and Hamilton 2005; Sterner and Persson 2008).

## Incomplete Treatment of Adaptation and Technological Change

Each of the three IAMs assumes a certain degree of adaptation.[29] Climate change will also increase returns on investment to develop technologies that help individuals to cope with

[28]It is important to note that crossing a climatic tipping point will not necessarily lead to an economic catastrophe in the sense used in the IAMs. A tipping point is a critical threshold beyond which some aspect of the earth's system starts to shift into a qualitatively different state (for instance, one with dramatically reduced ice sheet volumes and higher sea levels). In the IAMs, a catastrophe is a low-probability environmental change that would have a high economic impact.

[29]For instance, the largest single benefit category from GHG mitigation in FUND is the lower electricity costs from reduced air-conditioning usage (NRC 2009).

adverse climate conditions. For example, scientists may develop crops that are better able to withstand higher and more variable temperatures. Although DICE and FUND have calibrated their agricultural sectors under the assumption that farmers will change land use practices in response to climate change (Mastrandrea 2009), they do not take into account technological changes that lower the cost of this adaptation over time. Thus more research is needed for the IAMs to account adequately for this directed technological change.[30]

### Treatment of Risk Aversion

A key question that remained unanswered during the interagency process and demands further attention is what to assume about relative risk aversion with regard to high-impact outcomes.[31] The SCC estimates do not account for the possibility that individuals may have a higher willingness to pay to reduce the likelihood of low-probability, high-impact damages than to reduce the likelihood of higher-probability, lower-impact damages that have the same expected cost. Anthoff, Hepburn, and Tol (2009) conclude that "the assumed rate of risk aversion is at least as important as the assumed rate of time preference (a component of the discount rate) in determining the social cost of carbon."[32] This suggests that SCC estimates are also sensitive to assumptions about risk aversion. Nordhaus (2008) noted the need for further research on this issue in the context of climate change including exploring the relationship between risk and income across models and the impact of uncertainty regarding various parameters on the model results.

## Conclusions

Benefit–cost analysis is an important tool for assessing policies that affect $CO_2$ emissions, but it is not possible to conduct such an analysis adequately without a value for the SCC. The SCC enables us to monetize the economic value of the climate change–induced alterations in human health, ecosystems, agriculture, and other facets of life that result from a marginal change in $CO_2$ emissions, thus allowing us to compare the costs and the benefits of the avoided climate change associated with government policies. This makes it possible to distinguish more clearly between policies or regulations that have net benefits to society and those that have net costs.

This article has summarized the methodology used by a US government interagency group to develop SCC values for estimating the incremental global benefits of the $CO_2$ reductions associated with regulatory actions. These SCC values are the result of a technical and policy exercise designed to increase transparency and consistency in benefit–cost analyses of US government regulations. This process and methodology can also serve as a model for future revisions and updates of the SCC estimates.

As discussed earlier, for 2010, the central value of the SCC is \$21 per ton of $CO_2$ emissions, with sensitivity analysis to be conducted at \$5, \$35, and \$65. The \$5, \$21, and \$35 values are

[30]A full accounting of the benefits of this directed technical change would require accounting for the loss associated with reduced investment in areas that would otherwise have provided the highest expected returns.
[31]To our knowledge, the analysis of all other federal regulations assumes risk neutrality.
[32]Specifically, they used FUND to explore the sensitivity of the SCC to Ramsey equation parameter assumptions based on observed behavior.

averages calculated across a wide variety of models and scenarios for discount rates of 5, 3, and 2.5 percent, respectively. The $65 value—the 95th percentile of the SCC distribution at a 3 percent discount rate—represents the potential for higher than expected impacts from temperature change. These SCC estimates grow over time based on rates endogenously determined within each model.

The SCC values described here have quickly become integrated into the evaluation of national policy choices in the United States. In the short time since their release, these SCC values have been used to monetize the $CO_2$ emissions impacts of at least sixteen major US rules (those with costs or benefits above $100 million in any given year) across several federal agencies. The recent joint US Department of Transportation-EPA standards for GHG emissions and fuel efficiency for light-duty vehicles in model years 2012–16 (US EPA 2010b) illustrate the impact that the SCC can have on regulatory decisions. The upfront technology costs of the GHG rule for light-duty vehicles are estimated to be approximately $350 billion (in 2007 dollars) (US EPA 2010b). Before accounting for the impact of the rule on $CO_2$ emissions, societal benefits—which include the impact on energy security, refueling, local air pollutants, accidents, noise, and congestion—are estimated to be $280 billion (US EPA 2010b). Thus, before accounting for $CO_2$ emissions, the proposed rule would have a net cost of nearly $70 billion.[33] However, when the value of the $CO_2$ emissions reductions is incorporated into the benefit–cost analysis (using the interagency group's central SCC value), the proposed regulations are estimated to provide net societal benefits of more than $100 billion.

The SCC values are also making their way into public hearings and court cases. For example, the SCC was used in a Colorado Public Utility Commission hearing regarding Xcel Energy's plan to retire 900 megawatts of coal-fired generation to comply with state law (Keohane 2010a). More recently, the SCC was included in a declaration before the US Court of Appeals for the District of Columbia Circuit regarding EPA GHG regulations (Keohane 2010b).

Looking to the future, research and modeling improvements are needed so that the SCC estimates used in regulatory analysis by the US government continue to evolve and reflect current knowledge about the science and economics of climate impacts. Key areas for future research include improvements in how IAMs capture noncatastrophic and catastrophic impacts; increased focus on how predicted physical impacts translate into economic damages; a more complete treatment of behavioral assumptions concerning adaptation and technological changes that are induced by changing temperatures; analysis of how returns from investments in climate mitigation are correlated with investments in the economy overall; and development of appropriate methods for incorporating risk aversion. The role of the discount rate in regulatory analyses where the costs and benefits of a policy occur at different times also requires additional attention and discussion. As revisions to the SCC are considered in the future, it is also important to explore the sensitivity of the results to other aspects of the models (e.g., the carbon cycle). Finally, although most of the literature has focused on generating a social cost

[33]We have excluded any assessment of private fuel savings resulting from the rule because, although there is an emerging literature, many consider the question of how consumers account for fuel savings in their purchase decisions an unsettled empirical question (see Allcott and Greenstone 2012). Further, after accounting for the value of $CO_2$ emissions (using the central SCC value), this rule's benefits exceed its costs without making an assumption about consumer's behavior.

of carbon emissions, a methodology is also needed for valuing reductions in emissions of other GHGs.

## References

Allcott, H., and M. Greenstone. 2012. Is there an energy efficiency gap? *Journal of Economic Perspectives* 26 (1): 3–28.

Anthoff, D., C. Hepburn, and R. Tol. 2009. Equity weighting and the marginal damage costs of climate change. *Ecological Economics* 68: 836–49.

Arrow, K. 2007. Global climate change: A challenge to policy. *Economist's Voice* 4 (3): Article 2.

Arrow, K., W. Cline, K. Mäler, M. Munasinghe, R. Squitieri, and J. Stiglitz. 1996. Intertemporal equity, discounting and economic efficiency. In *Climate change 1995: Economic and social dimensions of climate change working group I contribution to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, ed. J. P. Bruce, H. Lee, and E. Haites, 128–44.

Becker, Gary S., Kevin M. Murphy, and Robert H. Topel. 2010. On the economics of climate policy. *Berkeley Electronic Journal of Economic Analysis & Policy* 10 (2) (Symposium): Article 19.

Bianco, N., and F. Litz. 2010. *Reducing greenhouse gas emissions in the United States using existing federal authorities and state action*. Washington, DC: World Resources Institute.

Bosetti, V., E. Massetti, and M. Tavoni. 2007. The WITCH model: Structure, baseline, solutions. Working paper. http://www.feem.it/getpage.aspx?id=1663&sez=Publications&padre=73 (accessed November 19, 2012).

Campbell, K., J. Gulledge, J. McNeill, J. Podesta, P. Ogden, L. Fuerth, J. Woolsey, A. Lennon, J. Smith, R. Weitz, and D. Mix. 2007. *The age of consequences: The foreign policy and national security implications of global climate change*. Washington, DC: Center for Strategic & International Studies.

Dasgupta, P. 2007. Commentary: The *Stern Review*'s economics of climate change. *National Institute Economic Review* 199: 4–7.

———. 2008. Discounting climate change. *Journal of Risk and Uncertainty* 37: 141–69.

Deshpande, M., and M. Greenstone. 2010. Comment on the economics of climate policy. *Berkeley Electronic Journal of Economic Analysis and Policy* 10 (2).

Groom, B., P. Koundouri, E. Panipoulou, and T. Pantelidis. 2007. Discounting the distant future: How much does model selection affect the certainty equivalent rate? *Journal of Applied Econometrics* 22 (3): 641–56.

Hall, R., and C. Jones. 2007. The value of life and the rise in health spending. *Quarterly Journal of Economics* 122 (1): 39–72.

Hansen, J., M. Sato, P. Kharecha, G. Russell, D. W. Lea, and M. Siddall. 2007. Climate change and trace gases. *Philosophical Transactions of the Royal Society A* 365: 1925–54.

Heal, G. 2009. Climate economics: A meta-review and some suggestions for future research. *Review of Environmental Economics and Policy* 3 (1): 4–21.

Hegerl, G., T. Crowley, W. Hyde, and D. Frame. 2006. Climate sensitivity constrained by temperature reconstructions over the past seven centuries. *Nature* 440: 1029–32.

Hope, C. 2006. The marginal impact of $CO_2$ from PAGE2002: An integrated assessment model incorporating the IPCC's five reasons for concern. *Integrated Assessment Journal* 6 (1): 19–56.

———. 2008. Optimal carbon emissions and the social cost of carbon under uncertainty. *Integrated Assessment Journal* 8 (1): 107–22.

Interagency Working Group on Social Cost of Carbon. 2010. *Social cost of carbon for regulatory impact analysis under executive order 12866*; Washington, DC. http://www.whitehouse.gov/sites/default/files/omb/inforeg/for-agencies/Social-Cost-of-Carbon-for-RIA.pdf (accessed November 19, 2012).

Intergovernmental Panel on Climate Change. 2007. In *Climate change 2007: The physical science basis, working group I contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press.

Keohane, N. 2010a. Answer testimony of Nathaniel Keohane, in the matter of commission consideration of Public Service Company of Colorado plan in compliance with House Bill 10-1365, Clean Air—Clean Jobs Act, Docket no. 10M-245E, September 17. http://www.dora.state.co.us/pls/efi/efi_p2_v2_demo.show_document?p_dms_document_id=75566 (accessed November 19, 2012).

———. 2010b. Declaration to United States Court of Appeals for the District of Columbia Circuit, October 31.

Kriegler, E., J. Hall, H. Held, R. Dawson, and H. Schellnhuber. 2009. Imprecise probability assessment of tipping points in the climate system. *Proceedings of the National Academy of Science* 106: 5041–46.

Lenton, T., H. Held, E. Kriegler, J. Hall, W. Lucht, S. Rahmstorf, and H. Schellnhuber. 2008. Tipping elements in the earth's climate system. *Proceedings of the National Academy of Science* 105: 1786–93.

Levy, M., S. Babu, and K. Hamilton. 2005. Ecosystem conditions and human well-being. In *Ecosystems and human well-being: Current state and trends*, Vol. 1, ed. R. Hassan, R. Scholes, and N. Ash, 123–64. Washington, DC: Island Press.

Mastrandrea, M. 2009. *Calculating the benefits of climate policy: Examining the assumptions of integrated assessment models*. Working Paper, Pew Center on Global Climate Change.

Meehl, G., T. Stocker, W. Collins, P. Friedlingstein, A. Gaye, J. Gregory, A. Kitoh, R. Knutti, J. Murphy, A. Noda, S. Raper, I. Watterson, A. Weaver, and Z-C Zhao. 2007. Global climate projections. In *Climate change 2007: The physical science basis*, ed. S. Solomon, D. Qin, M. Manning, M. Marquis, K. Averyt, M. Tignor, H. Miller, and Z. Chen. Geneva, Switzerland: Intergovernmental Panel on Climate Change.

National Research Council (NRC). 2009. *Hidden costs of energy: Unpriced consequences of energy production and use*. Washington, DC: National Academies Press.

Newbold, S., and A. Daigneault. 2009. Climate response uncertainty and the benefits of greenhouse gas emissions reductions. *Environmental and Resource Economics* 44: 351–77.

Newell, R., and W. Pizer. 2003. Discounting the distant future: How much do uncertain rates increase valuations? *Journal of Environmental Economics and Management* 46: 52–71.

Nordhaus, W. 2008. *A question of balance: Weighing the options on global warming policies*. New Haven, CT: Yale University Press.

———. 2009. An analysis of the dismal theorem. Cowles Foundation discussion paper no. 1686. January.

Nordhaus, W., and J. Boyer. 2000. *Warming the world: Economic models of global warming*. Cambridge, MA: MIT Press.

Office of Management and Budget (OMB). 2003. *Circular A-4: Regulatory analysis*. September.

Pindyck, R. 2012. Uncertain outcomes and climate change policy. *Journal of Environmental Economics and Management* 63 (3): 289–303.

Portney, P., and J. Weyant. 1999. *Discounting and intergenerational equity*. Washington, DC: Resources for the Future.

Ramsey, F. P. 1928. A mathematical theory of saving. *Economic Journal* 38 (152): 543–59.

Roe, G. 2008. Feedbacks, timescales, and seeing red. *Annual Review of Earth and Planetary Sciences* 37: 5.1–5.23.

Roe, G., and M. Baker. 2007. Why is climate sensitivity so unpredictable? *Science* 318: 629–32.

Stern, N. 2007. *The economics of climate change: The* Stern Review. Cambridge and New York: Cambridge University Press.

———. 2008. The economics of climate change. *American Economic Review* 98 (2): 1–37.

Sterner, T., and U. Persson. 2008. An even sterner review: Introducing relative prices into the discounting debate. *Review of Environmental Economics and Policy* 2 (1): 61–76.

Szpiro, G. 1986. Measuring risk aversion: An alternative approach. *Review of Economics and Statistics* 68 (1): 156–59.

Tol, R. 2002a. Estimates of the damage costs of climate change. Part I: Benchmark estimates. *Environmental and Resource Economics* 21: 47–73.

Tol, R. 2002b. Estimates of the damage costs of climate change. Part II: Dynamic estimates. *Environmental and Resource Economics* 21: 135–60.

———. 2009. *An analysis of mitigation as a response to climate change*. Copenhagen Consensus on Climate discussion paper.

US Department of Defense. 2010. Quadrennial defense review report. February.

US Environmental Protection Agency (EPA). 2010a. Discounting future costs and benefits. *Guidelines for preparing economic analyses*. EPA 240-R-10-001.

US Environmental Protection Agency (EPA). 2010b. Final rulemaking to establish light-duty vehicle greenhouse gas emission standards and corporate average fuel economy standards. Regulatory impact analysis, http://www.epa.gov/oms/climate/regulations/420r10009.pdf (accessed November 19, 2012).

Weitzman, M. 1998. Why the far-distant future should be discounted at its lowest possible rate. *Journal of Environmental Economics and Management* 36 (3): 201–8.

———. 1999. In *Discounting and intergenerational equity: resources for the future*, ed. P. R. Portney, and J. P. Weyant, Washington, DC.

———. 2007. The *Stern Review* of the economics of climate change. *Journal of Economic Literature* 45 (3): 703–24.

———. 2009. On modeling and interpreting the economics of catastrophic climate change. *Review of Economics and Statistics* 91: 1–19.