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May 2011

CEEPR WP 2011-006

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* The views expressed in this paper are those of the authors and do not necessarily represent those of the U.S. Environmental Protection Agency or the Massachusetts Institute of Technology. Elizabeth Kopits and Ann Wolverton are economists at the U.S. Environmental Protection Agency. Michael Greenstone is a professor at the Massachusetts Institute of Technology. They all worked at 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.

**Estimating the Social Cost of Carbon for Use in U.S. Federal Rulemakings:
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ABSTRACT

The United States Government recently concluded a year-long process to develop a range of values representing the monetized damages associated with an incremental increase in carbon dioxide (CO₂) emissions, commonly referred to as the social cost of carbon (SCC). These values are currently used in benefit-cost analyses to assess potential federal regulations. For 2010, the central value of the SCC is \$21 per ton of CO₂ emissions and sensitivity analyses are to be conducted at \$5, \$35, and \$65 (2007\$). This paper summarizes the methodology and process used to develop the SCC values, complemented with our own commentary about how the SCC can be used to inform regulatory decisions and areas where further research would be particularly useful.

JEL Codes: Q54, Q51, and Q58

Keywords: climate change; social cost of carbon; integrated assessment modeling; valuation of environmental quality; U.S. climate policy

I. Introduction

The climate is a key ingredient in the Earth's complex system that sustains human life and wellbeing. According to the United Nation's Intergovernmental Panel on Climate Change (IPCC), the emissions of greenhouse gases (GHG) due to human activity, largely combustion of fossil fuels such as coal, are "very likely" altering the earth's climate, most notably by increasing temperature, changing precipitation patterns and increasing weather variability. Without coordinated policy around the globe, state-of-the-art climate models predict that the mean temperature in the United States will increase by about 3 to 8 °F (1.7 to 4.4 °C) by the end of the century compared to today (IPCC 2007). Further, the distribution of daily temperatures is projected to increase in ways that pose serious challenges to wellbeing; for example, the number of days per year when the typical American will experience a mean (average of the minimum and maximum) temperature that exceeds 90 °F is projected to increase from the current 1.3 days to 32.2 days (Deschenes and Greenstone, forthcoming).

Over the past several years, it appeared that the United States and possibly other major emitters were poised to confront climate change by adopting a coordinated set of policies that could have included linked cap-and-trade systems. However, the failure of the United States to institute such a system domestically and the non-binding commitments from the Copenhagen Accord seem to have placed such a solution to climate change out of reach for at least several years.

Instead, the United States and many other countries are likely to pursue a series of smaller policies, all of which aim to reduce GHG emissions but individually are expected to have only a marginal impact on atmospheric concentrations. These policies will appear in a wide variety of domains, 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. Although many of these policies have other goals, there may be increased use of them as a means of reducing GHG emissions. Note that these policies will reduce GHG emissions at different rates and at different costs.

In the presence of the nearly limitless potential policies to reduce GHG emissions, how is government to set out a rational climate policy? The key step is to determine the monetized damages associated with an incremental increase in carbon emissions, which is referred to as the social cost of carbon (SCC).¹ It is intended to include (but is not limited to) changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services. Monetized estimates of the economic damages associated with

¹ Under Executive Order 12866, agencies in the Executive branch of the U.S. Federal government are required, to the extent permitted by law, "to assess both the costs and the benefits of the intended regulation and, recognizing that some costs and benefits are difficult to quantify, propose or adopt a regulation only upon a reasoned determination that the benefits of the intended regulation justify its costs."

carbon dioxide (CO₂) emissions allow the social benefits of regulatory actions that are expected to reduce these emissions to be incorporated into cost-benefit analyses.² Indeed, as the Environmental Protection Agency begins to regulate greenhouse gases under the Clean Air Act, the SCC can help to identify the regulations where the net benefits are positive.

The United States government recently developed four SCC estimates for use in regulatory analyses and has been using them regularly since their release (Interagency Working Group 2010). For 2010, the central value is \$21 per ton of CO₂ emissions and sensitivity analysis is to be conducted at \$5, \$35, and \$65.³ The \$21, \$5, and \$35 values are based on the average SCC across the models and scenarios examined for the 5, 3, and 2.5 percent discount rates, respectively. The \$65 value—the 95th percentile of the SCC distribution at a 3 percent discount rate—was chosen to represent potential higher-than-expected impacts from temperature change. These SCC estimates also grow over time based on rates endogenously determined within each model. For instance, the central value increases to \$24 per ton of CO₂ in 2015 and \$26 per ton of CO₂ in 2020.

The 2009-2010 interagency process that developed these SCC values was the first U.S. federal government effort to promote consistency in the way that agencies calculate the social benefits of reducing CO₂ emissions in regulatory impact analyses.⁴ Prior to 2008, reductions in CO₂ emissions were not valued in federal benefit–cost analyses. From 2008 to 2009, SCC estimates were used in some regulatory analyses, but the values employed varied substantially among agencies. The interagency process aimed to develop a defensible, transparent, and economically rigorous way to value reductions in CO₂ emissions that result from Federal regulations. Specifically, the goal was to develop a range of SCC values in a way that used a defensible set of input assumptions, was grounded in the existing literature, and allowed key uncertainties and model differences to transparently and consistently inform the range of SCC estimates used in the rulemaking process.

We, the authors of this article, were involved in the interagency effort and the intent of this article is to summarize the group’s efforts – in many instances, borrowing language directly from

² Most regulatory actions are expected to have small, or “marginal,” impacts on cumulative global emissions, making the use of SCC an appropriate measure.

³ All values of the SCC are presented as the cost per metric ton of carbon dioxide (CO₂) emissions and are expressed in 2007 dollars.

⁴ Much of what is summarized in the body of this article is taken directly from the interagency working group report, which can be read in full at <http://www.whitehouse.gov/sites/default/files/omb/inforeg/for-agencies/Social-Cost-of-Carbon-for-RIA.pdf>. The document is authored by a wider set of analysts than conveyed by the authorship of this summary article. The interagency process was convened by the Council of Economic Advisers and the Office of Management and Budget, with regular input from other offices within the Executive Office of the President, including the Council on Environmental Quality, National Economic Council, Office of Energy and Climate Change, and Office of Science and Technology Policy. Agencies that actively participated included the Environmental Protection Agency, and the Departments of Agriculture, Commerce, Energy, Transportation, and Treasury.

the interagency report - complemented with some of our own commentary, especially about how the SCC can be used to inform regulatory decisions. We hope readers of this paper will help to fill the research gaps identified by the interagency group and summarized in this paper so that the next effort to revise these values retains its rigor while improving upon the methodology described herein. The interagency group explicitly aims to periodically update the current set of SCC estimates to reflect scientific and economic advances.

The remainder of the paper is organized as follows. Section II provides background on integrated assessment models (IAMs) and describes key modeling assumptions used to develop the SCC. Section III presents and discusses the estimation process and resulting values. We highlight ways in which the SCC has already been applied in national decision-making in Section IV. Areas of future research are summarized in Section V. Section VI concludes. Sections II, III, and V draw especially heavily from the interagency report.

II. Integrated Assessment Models and Key Assumptions

Analysts face a number of significant challenges when attempting to quantify the economic impacts of CO₂ emissions. In particular, analysts must make assumptions about four main steps of the estimation process: (1) the future emissions of greenhouse gases; (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. Integrated assessment models (IAMs) have been developed to combine these steps into a single modeling framework; the word “integrated” refers to the fact that they integrate knowledge from science and economics. However, they gain this advantage at the expense of a more detailed representation of the underlying climatic and economic systems.

This section describes the IAMs and the common set of modeling assumptions the interagency group used to develop the SCC.

A. Background on IAMs and their Damage Functions

The interagency group relied on three IAMs commonly used to estimate the SCC: the FUND, DICE, and PAGE models.⁵ These models are frequently cited in the peer-reviewed literature and are used in the IPCC assessment. Each model was given equal weight in the SCC values developed through this process, bearing in mind their different limitations.

⁵ The DICE (Dynamic Integrated Climate and Economy) model by William Nordhaus evolved from a series of energy models and was first presented in 1990 (Nordhaus and Boyer 2000, Nordhaus 2008). The PAGE (Policy Analysis of the Greenhouse Effect) model was developed by Chris Hope in 1991 for use by European decision-makers in assessing the marginal impact of carbon emissions (Hope 2006, Hope 2008). The FUND (Climate Framework for Uncertainty, Negotiation, and Distribution) model, developed by Richard Tol in the early 1990s, originally to study international capital transfers in climate policy is now widely used to study climate impacts (e.g., Tol 2002a, Tol 2002b, Anthoff et al. 2009, Tol 2009a, Tol 2009b).

DICE, PAGE, and FUND all take stylized, reduced-form approaches (see NRC 2009 and Nordhaus 2008). Other IAMs may better reflect the complexity of the science in their modeling frameworks but do not link physical impacts to economic damages. Underlying the three IAMs selected for this exercise are a number of simplifying assumptions and judgments reflecting the various modelers' best attempts to synthesize the available scientific and economic research characterizing these relationships.

The three IAMs translate emissions into changes in atmospheric greenhouse gas concentrations, atmospheric concentrations into changes in temperature, and changes in temperature into economic damages. The emissions projections used in the models are based on specified socio-economic (GDP and population) pathways. These emissions are translated into concentrations using the carbon cycle built into each model, and concentrations are translated into warming based on each model's simplified representation of the climate and a key parameter, climate sensitivity. Finally, transforming the stream of economic damages over time into a single value requires judgments about how to discount them.

Each model takes a slightly different approach to model how changes in emissions result in changes in economic damages. In PAGE, for example, the consumption-equivalent damages in each period are calculated as a fraction of GDP, depending on the temperature in that period relative to the pre-industrial average temperature in each region. In FUND, damages in each period also depend on the rate of temperature change from the prior period. In DICE, temperature affects both consumption and investment.

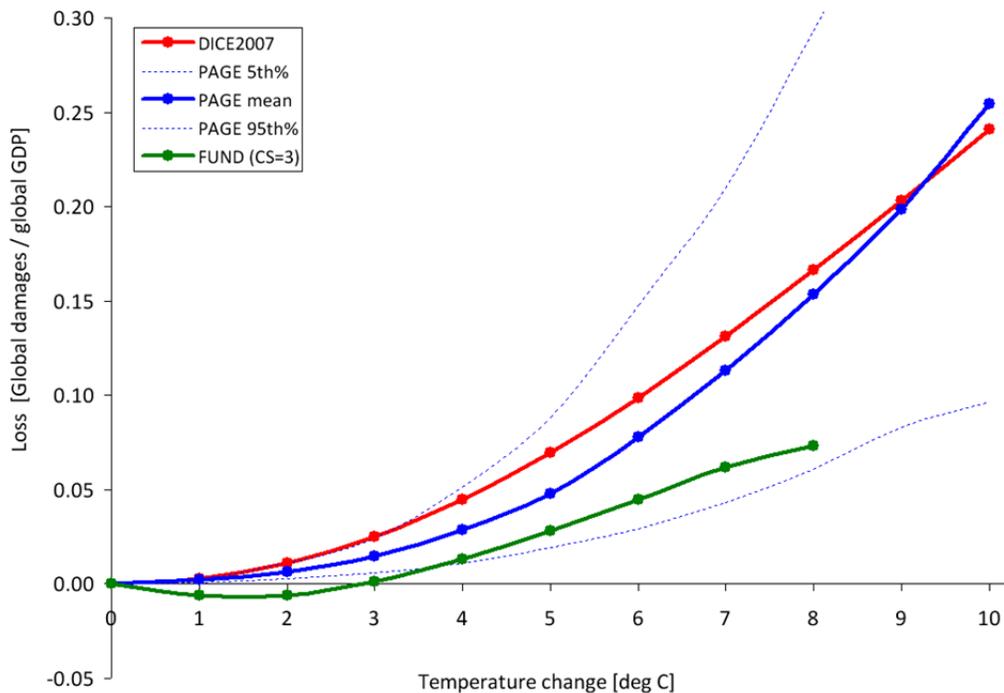
The three damage functions are presented in Figure 1, using the modeler's default scenarios and mean input assumptions.⁶ The x-axis represents increases in annual temperature in 2100, while the y-axis represents the annual consumption loss in 2100 as a share of global GDP. Significant differences between the three models are evident at both lower and higher increases in global-average temperature.

The FUND damage function predicts that temperature increases up to about 3 °C are beneficial. This is in part because FUND allows for greater adaptation (and therefore lower damages) when climate change happens more slowly. The combined effect of CO₂ fertilization in the agricultural sector, positive impacts to some regions from higher temperatures, and sufficiently slow increases in temperature across these sectors can result in negative economic damages from climate change. At higher temperature increases, FUND is notable for its exclusion of catastrophic damages.

⁶ Each specific combination of climate sensitivity, socio-economic, and emissions parameters produces a different realization of damages for each IAM. The damage functions represented in Figure 1 are the outcome of default assumptions. For instance, under alternate assumptions, the damages from FUND may cross from negative to positive at less than or greater than 3 °C. Note the graph shows annual temperature, not equilibrium temperature.

The DICE and PAGE damage functions are similar but project substantially larger losses across the range of temperatures. Both include the possibility of catastrophic damages at higher temperatures. For instance, PAGE models the threshold temperature, the rate at which the probability of experiencing a discontinuity increases above the threshold, and the magnitude of the resulting catastrophe. PAGE and DICE also differ from FUND in their assumptions regarding adaptation. For instance, PAGE assumes that the developed countries can ultimately eliminate up to 90 percent of all economic impacts beyond the tolerable 2 °C increase and that developing countries can eventually eliminate 50 percent of their economic impacts. The DICE model does not contain structural components that represent adaptation explicitly, though it is included implicitly through the choice of studies used to calibrate the aggregate damage function.

Figure 1: Annual Consumption Loss as a Fraction of Global GDP in 2100 Due to an Increase in Annual Global Temperature in the DICE, FUND, and PAGE models



Source: Figure 1A, Interagency report. EPA analysts estimated the damage functions using the default assumptions available in each model. These damage functions do not reflect the interagency group's assumptions that differ from those used by the relevant model developer nor the probabilistic treatment of various parameters in FUND or DICE.

It is also worth noting that the models vary in what is treated probabilistically. In DICE, parameters are handled deterministically and represented by fixed constants; in PAGE, most parameters are represented by probability distributions. For this exercise, parameters in FUND were also treated probabilistically.

Overall, the power of the IAMs is that they offer guidance to the incredibly complex question of what an extra ton of greenhouse damages will do to human wellbeing. This is no small task and this is what makes them so appealing. However, the results are highly dependent on a series of assumptions that cannot easily be verified. Indeed, the evident differences across the damage functions underscore the need for a thorough review of damage functions to better understand how the models incorporate adaptation, technological change, and catastrophic damages. Section V highlights key gaps in how the models account for various scientific and economic processes.

B. Key Modeling Assumptions of the Interagency Group

The parameters and assumptions embedded in the three models also vary widely. A key objective of the interagency process was to enable a consistent exploration of the three models while respecting the different approaches to quantifying damages taken by the main modelers in the field. An extensive review of the literature was conducted to select three sets of input parameters for these models: climate sensitivity, socio-economic and emissions trajectories, and discount rates. A probability distribution for climate sensitivity was specified as an input into all three models. In addition, the interagency group used a range of scenarios for the socio-economic parameters and a range of values for the discount rate. All other model features were left unchanged, relying on the model developers' best estimates and judgments, including how to represent the effects of climate change (represented by the increase in global-average surface temperature) on the consumption-equivalent value of both market and non-market goods (represented as a fraction of global GDP).

1. Socio-economic and Emissions Trajectories. Socio-economic pathways are closely tied to climate damages because, all else equal, more and wealthier people tend to emit more greenhouse gases and also have a higher (absolute) willingness to pay to avoid climate disruptions. For this reason, it is standard to model several input parameters in tandem: GDP, population, CO₂ emissions, and non-CO₂ radiative forcing. A wide variety of scenarios have been developed and used for climate change policy simulations (e.g., IPCC Special Report on Emissions Scenarios (SRES) 2000, U.S. Climate Change Science Program (CCSP) 2007, Stanford Energy Modeling Forum (EMF) 2009). In determining which scenarios are appropriate for inclusion, the interagency group aimed to select scenarios that span most of the plausible ranges of outcomes for these variables.

To accomplish this task in a transparent manner, the interagency group relied on the Stanford Energy Modeling Forum exercise, EMF-22. EMF-22 uses ten well-recognized models to evaluate substantial, coordinated global action to meet specific stabilization targets. A key advantage of relying on these data is that GDP, population, and emission trajectories are internally consistent for each model and scenario evaluated. The EMF-22 modeling effort also is

preferable to the IPCC SRES due to their age (SRES were developed in 1997) and the fact that 3 of 4 of the SRES scenarios are now extreme outliers in one or more variables. Although the EMF-22 scenarios have not undergone the same level of scrutiny as the SRES scenarios, they are recent, peer-reviewed, published, and publicly available.

Five trajectories were selected from EMF-22 (see Table 1) and were given equal weight in the derivation of the SCC. Four of these represent potential business-as-usual (BAU) growth in population, wealth, and emissions and are associated with CO₂ (only) concentrations ranging from 612 to 889 parts per million (ppm) in 2100. The fifth represents an emissions pathway that achieves stabilization at 550 ppm CO₂e (i.e., CO₂-only concentrations of 425 – 484 ppm or a radiative forcing of 3.7 W/m²) in 2100, a lower-than-BAU trajectory.⁷ Out of the ten models included in the EMF-22 exercise, the interagency group used the GDP, population, and emission BAU trajectories predicted by the MiniCAM, MESSAGE, and IMAGE models, and the optimistic scenario from the MERGE model.⁸ For the 550 ppm CO₂e scenario, the group averaged the GDP, population, and emission trajectories implied by these same four models.⁹

Table 1: Socioeconomic and Emissions Projections from Select EMF-22 Reference Scenarios

A. Fossil and Industrial CO₂ Emissions (GtCO₂/yr)

EMF – 22 Based Scenarios	2000	2050	2100	Annualized % Change	
				2000-2050	2050-2100
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\$)

EMF – 22 Based Scenarios	2000	2050	2100	Annualized % Change	
				2000-2050	2050-2100
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%

⁷ Such an emissions path would be consistent with widespread action by countries to mitigate GHG emissions, though it could also result from technological advances.

⁸ The MiniCAM model is developed by the Joint Global Change Research Institute (JCGRI - Pacific Northwest National Laboratory and the University of Maryland), MESSAGE is developed by the International Institute for Applied Systems Analysis (IIASA), IMAGE is developed by the Netherlands Environmental Assessment Agency (MNP, formerly RIVM), and MERGE is housed at Stanford University.

⁹ The interagency group considered formally assigning probability weights to different states of the world, but this proved challenging to do in an analytically rigorous way given the dearth of information on the likelihood of a full range of future socio-economic pathways. Of course, giving equal weighting to each of the five scenarios is identical to placing a probability of 0.2 on each of the scenarios.

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)

EMF – 22 Based Scenarios	Annualized % Change				
	2000	2050	2100	2000-2050	2050-2100
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%

*Average of the GDP, population, and emission trajectories implied by IMAGE, MERGE Optimistic, MESSAGE, and MiniCAM under the 550 ppm CO₂-e full participation, not to exceed, stabilization scenario considered by EMF-22.

Source: The socioeconomic scenarios are available through Stanford’s Energy Modeling Forum (EMF):

http://emf.stanford.edu/events/emf_briefing_on_climate_policy_scenarios_us_domestic_and_international_policy_architectures/. The models were calibrated off a 2000 base year.

There are several noteworthy details here. First, the EMF BAU scenarios represent the modelers’ judgment of a likely pathway absent mitigation policies to reduce greenhouse gas emissions, rather than the wider range of possible outcomes. Nevertheless, these views span a wide 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).¹⁰ Second, the emission trajectories underlying some BAU scenarios (e.g., MESSAGE’s Optimistic scenario) also are consistent with modest policy action to address climate change. Third, the socio-economic trajectories associated with a 550 ppm CO₂e concentration scenario are not derived from an assessment of what policy is optimal from a benefit-cost standpoint. Rather, it is indicative of one possible future outcome. The group chose not to include socio-economic trajectories that achieve even lower GHG concentrations at this time, given the difficulty many models had in converging to meet these targets.¹¹

2. Equilibrium Climate Sensitivity. Equilibrium climate sensitivity (ECS) is a key input parameter for the DICE, PAGE, and FUND models. It is defined as the long-term increase in the annual global-average surface temperature from a doubling of atmospheric CO₂ concentration,

¹⁰ For instance, in the MESSAGE model’s reference case, total primary energy production from nuclear, biomass, and non-biomass renewables is projected to increase from about 15 percent of total primary energy in 2000 to 54 percent in 2100. In comparison, the MiniCAM reference case shows 10 percent in 2000 and 21 percent in 2100.

¹¹ In addition to fossil and industrial CO₂ emissions, each EMF scenario provides projections of methane, nitrous oxide, fluorinated greenhouse gases, and net land use CO₂ emissions out to 2100. These assumptions are used in the three models while retaining the default radiative forcings due to other factors (e.g., aerosols and other gases).

relative to pre-industrial levels (or stabilization at a concentration of approximately 550 ppm).¹² Uncertainties in this important parameter have received substantial attention in the peer-reviewed literature.

The most authoritative statement about equilibrium climate sensitivity 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 CO₂, 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.*¹³

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, p 799)

After consulting with several lead authors of this chapter of the IPCC report, the interagency group selected four candidate probability distributions and calibrated them to be consistent with the above statement: Roe and Baker (2007), log-normal, gamma, and Weibull. Table 2 gives summary statistics for the four calibrated distributions.

Table 2: Summary Statistics for Four Calibrated Climate Sensitivity Distributions

	Roe & Baker	Log-normal	Gamma	Weibull
Pr(ECS < 1.5°C)	0.013	0.050	0.070	0.102
Pr(2°C < ECS < 4.5°C)	0.667	0.667	0.667	0.667
5 th percentile	1.72	1.49	1.37	1.13
10 th percentile	1.91	1.74	1.65	1.48
Mode	2.34	2.52	2.65	2.90
Median (50 th percentile)	3.00	3.00	3.00	3.00
Mean	3.50	3.28	3.19	3.07
90 th percentile	5.86	5.14	4.93	4.69

¹² The equilibrium climate sensitivity includes the response of the climate system to increased greenhouse gas concentrations over the short to medium term (up to 100-200 years), but it does not include long-term feedback effects due to possible large-scale changes in ice sheets or the biosphere, which occur on a time scale of many hundreds to thousands of years (e.g., Hansen et al. 2007).

¹³ The IPCC definition of “likely” as greater than 66 percent probability (Le Treut et al. 2007). “Very likely” indicates a greater than 90 percent probability.

95 th percentile	7.14	5.97	5.59	5.17
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Source: Table 1, Interagency report.

Each distribution was calibrated by applying three constraints from the IPCC:

- (1) a median equal to 3 °C, to reflect the judgment of “a most likely value of about 3 °C”;¹⁴
- (2) two-thirds probability that the equilibrium climate sensitivity 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, p. 721).

The interagency group selected the calibrated Roe and Baker distribution from the four candidates for two reasons. First, the Roe and Baker distribution is the only one of the four that is based on a theoretical understanding of the response of the climate system to increased greenhouse gas concentrations (Roe and Baker 2007, Roe 2008). In contrast, the other three distributions are mathematical functions that are arbitrarily chosen based on simplicity, convenience, and general shape. The Roe and Baker distribution results from three assumptions about climate response: (i) absent feedback effects, the equilibrium climate sensitivity is equal to 1.2 °C; (ii) feedback factors are proportional to the change in surface temperature; and (iii) uncertainties in feedback factors are normally distributed. There is widespread agreement on the first point and the second and third points are common assumptions.

Second, the calibrated Roe and Baker distribution better reflects the IPCC judgment that “values substantially higher than 4.5 °C still cannot be excluded.” Although the IPCC made no quantitative judgment, the 95th percentile of the calibrated Roe and Baker distribution (7.1 °C) is much closer to the mean and the median (7.2 °C) of the 95th percentiles of 21 previous studies summarized by Newbold and Daigneault (2009). It is also closer to the mean (7.5 °C) and median (7.9 °C) of the nine truncated distributions examined by the IPCC (Hegerl, et al., 2006) than are the 95th percentiles of the three other calibrated distributions (5.2-6.0 °C).

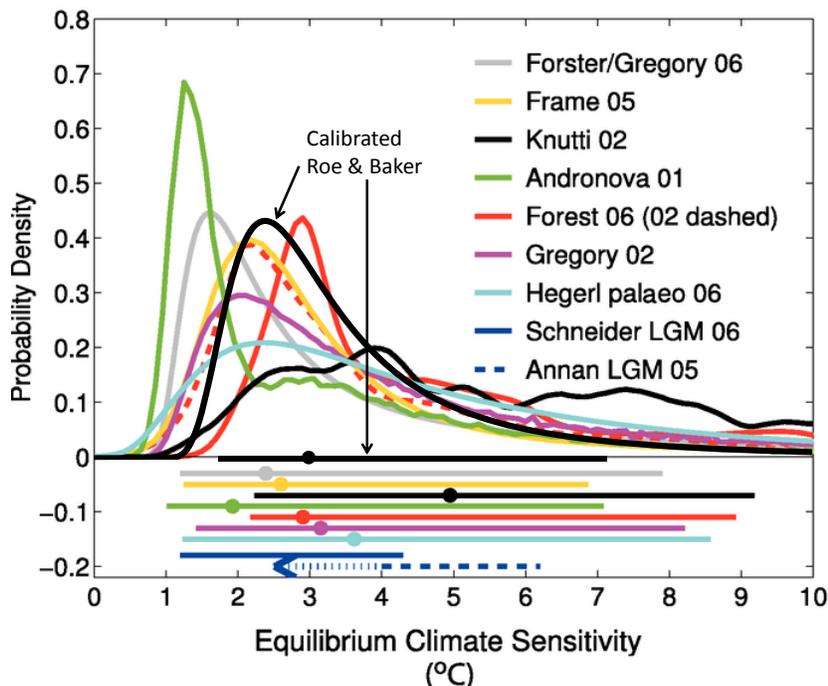
Finally, the IPCC stated that the equilibrium climate sensitivity “is very likely larger than 1.5 °C”. Although the calibrated Roe and Baker distribution, for which the probability of equilibrium

¹⁴ Strictly speaking, “most likely” refers to the mode of a distribution rather than the median, but common usage would allow the mode, median, or mean to serve as candidates for the central or “most likely” value and the IPCC report is not specific on this point. For the distributions we considered, the median was between the mode and the mean. For the Roe and Baker distribution, setting the median equal to 3 °C, rather than the mode or mean, gave a 95th percentile that is more consistent with IPCC judgments and the literature. For example, setting the mean and mode equal to 3 °C produced 95th percentiles of 5.6 and 8.6 °C, respectively, which are in the lower and upper end of the range in the literature. Finally, the median is closer to 3 °C than is the mode for the truncated distributions selected by the IPCC (Hegerl, et al., 2006); the average median is 3.1 °C and the average mode is 2.3 °C, which is most consistent with a Roe and Baker distribution with the median set equal to 3 °C.

climate sensitivity being greater than 1.5 °C is almost 99 percent, is not inconsistent with the IPCC definition of “very likely” as “greater than 90 percent probability,” it reflects a greater degree of certainty about very low values of equilibrium climate sensitivity than was expressed by the IPCC.

To show how the calibrated Roe and Baker distribution compares to different estimates of the probability distribution function of equilibrium climate sensitivity in the empirical literature, Figure 2 overlays it on distributions estimated in other recent studies. These functions are scaled to integrate to unity between 0 °C and 10 °C. The horizontal bars show the respective 5 percent to 95 percent ranges; dots indicate the median estimate.

Figure 2: Estimates of the Probability Density Function for Equilibrium Climate Sensitivity (°C)



Source: Figure 2, Intergovernmental Panel on Climate Change (IPCC) report. This graph displays Figure 9.20 from IPCC (2007), plus the calibrated Roe and Baker distribution on the IPCC graphic for comparison purposes.

3. Discount Rates. The discount rate is intended to reflect society's marginal rate of substitution between consumption in different time periods. For rules with both intra- and intergenerational effects, Federal agencies traditionally employ constant discount rates of 3 and 7 percent (OMB 2003). However, the choice of a discount rate over especially long periods of time raises highly contested and exceedingly difficult questions of science, economics, philosophy, and law.

Discounting plays a critical role in determining the SCC estimates. To see this, note that the SCC is calculated by first estimating the damages from an additional unit of CO₂ emitted in a particular year in terms of reduced consumption due to the impacts of elevated temperatures into the future. Because CO₂ has a half life of approximately 100 years, the damages from a unit of emissions occur over many decades. The selected 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 two main approaches to determine the discount rate for climate change analysis, which they labeled “descriptive” and “prescriptive”. The descriptive approach reflects a positive (non-normative) perspective based on observations of people’s actual choices—e.g., savings versus consumption decisions over time, and allocations of savings among more and less risky investments. Advocates of this approach generally call for inferring the discount rate from market rates of return. The prescriptive approach specifies a social welfare function that formalizes the normative judgments that the decision-maker wants explicitly to incorporate into the policy evaluation—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.¹⁵

Historically Observed Interest Rates

Advocates of the descriptive approach generally call for inferring the discount rate from observed market rates of return “because of a lack of justification for choosing a social welfare function that is any different than what decision makers [individuals] actually use” (Arrow et al. 1996). The standard analytic framework used to develop intuition about the discount rate typically assumes a representative agent with perfect foresight and no credit constraints. However, individuals use a variety of savings instruments with associated interest rates that vary with risk level, time horizon, and tax characteristics. For example, the interest rate associated with holding equity, gold, commodities, and riskless Treasury bonds vary greatly, so there is not a single interest rate to appeal to as is often assumed in economic models.

Is one of these interest rates best suited for discounting in the context of climate change? Recall, an expenditure today to mitigate greenhouse gas emissions that is financed out of current consumption is like any other investment. Its return is measured in the higher level of

¹⁵ One theoretical foundation for the cost-benefit analyses in which the social cost of carbon will be used—the Kaldor-Hicks potential-compensation test—also suggests that market rates should be used to discount future benefits and costs, because it is the market interest rate that would govern the returns potentially set aside today to compensate future individuals for climate damages that they bear (e.g., Just et al. 2004). As some have noted, the word “potentially” is an important qualification; there is no assurance that such returns will actually be set aside to provide compensation, and the very idea of compensation is difficult to define in the intergenerational context. On the other hand, societies provide compensation to future generations through investments in human capital and the resulting increase in knowledge, as well as infrastructure and other physical capital.

consumption available in the future due to reduced changes in climate, for example smaller temperature increases. Indeed, the treatment of climate mitigation as an investment with an uncertain return underscores the logic of using a market interest rate for the discount rate. In this light, it is evident that climate mitigation should be compared with standard public investments that increase the wellbeing of future generations and that, in fact, future generations would want the current generation to make investment choices in this manner.

The crucial question then is how the returns to climate mitigation co-vary with the returns to the uncertain returns to investments in the overall economy, which is frequently proxied by overall equity returns.¹⁶ There are three focal cases worth considering. The first case is when the returns are perfectly correlated with the economy's overall growth rate, which would be the case if the damages from climate change are a fixed share of GDP. In this case, the proper discount rate is the expected return on investments in the economy as a whole.

The second case is when the returns to climate mitigation investments are orthogonal to the economy's overall growth rate. Here, the appropriate discount rate is the riskless interest rate.

The third case is when the returns to climate mitigation are negatively correlated with the economy's growth rate. So, for example, a climate mitigation project may pay off in states of the world where the overall economy is doing poorly and the marginal utility of an additional unit of consumption is especially high. In this case, these investments have a low expected return but pay off when it is most valuable. In this case, it would be appropriate to use discount rates that are smaller than the riskless rate.¹⁷ Thus, depending on the correlation between mitigation investments and the overall economy, it is possible to defend the setting of the discount rate equal to the post-tax equity return, post-tax riskless return, and even rates below the post-tax riskless rate.

The Ramsey Equation

Ramsey discounting also provides a useful framework to inform the choice of a discount rate. Under this approach, the analyst applies either positive or normative judgments in selecting values for the key parameters of the Ramsey equation: η (coefficient of relative risk aversion or elasticity of the marginal utility of consumption) and ρ (pure rate of time preference).¹⁸ These

¹⁶ The correlation between these investments and overall economy-wide growth can be thought of like the Beta in the CAPM model, which measures how changes in market returns affect an individual investment's returns. Becker, Murphy, and Topel (2011) and Weitzman (2007) have insightful discussions of these issues.

¹⁷ Heal (2009) and Sterner and Persson (2008) also point out that if models do not properly account for the depletion of natural capital resulting from climate change, then market rates will be biased upwards. Climate policy is also justified as a form of insurance to avoid the small chance of a large catastrophe far out in the future (Weitzman 2007).

¹⁸ The parameter η captures *diminishing marginal utility*: consumption in the future is likely to be higher than consumption today, so diminishing marginal utility of consumption implies that the same monetary damage will

are then combined with g (growth rate of per-capita consumption) to equal the interest rate at which future monetized damages are discounted: $\rho + \eta \cdot g$.

Most papers in the climate change literature adopt values for η in the range of 0.5 to 3, although not all authors articulate whether their choice is based on prescriptive or descriptive reasoning.¹⁹ Dasgupta (2008) argues that η should be greater than 1 and may be as high as 3, since η equal to 1 suggests savings rates that do not conform to observed behavior. With respect to the pure rate of time preference, most papers in the climate change literature adopt values for ρ in the range of 0 to 3 percent per year. The very low rates tend to follow from moral judgments involving intergenerational neutrality. Some have argued that to use any value other than $\rho = 0$ would unjustly discriminate against future generations (e.g., Arrow et al. 1996, Stern et al. 2006). However, even in an inter-generational setting, it may make sense to use a small positive pure rate of time preference because of the small probability of unforeseen cataclysmic events (Stern et al. 2006).

Some economists and non-economists have argued for constant discount rates below 2 percent based on the prescriptive approach. When grounded in the Ramsey framework, proponents of this approach have argued that a ρ of zero avoids giving preferential treatment to one generation over another. The choice of η has also been posed as an ethical choice linked to the value of an additional dollar in poorer countries compared to wealthier ones. Stern et al. (2006) applies this perspective through his choice of $\rho = 0.1$ percent per year $\eta = 1$, yielding an annual discount rate of 1.4 percent when combined with the growth rate. Recently, Stern (2008) revisited the values used in Stern et al. (2006), stating that there is a case to be made for raising η due to the amount of weight lower values place on damages far in the future (over 90 percent of expected damages occur after 2200 with $\eta = 1$).

Uncertainty in the Discount Rate

While the consumption rate of interest is an important driver of the benefits estimate, it is uncertain over time. Ideally, one would formally model this uncertainty. Weitzman (1998) showed theoretically and Newell and Pizer (2003) and Groom et al. (2006) confirm empirically that discount rate uncertainty can have a large effect on net present values. A main result from these studies is that if there is a persistent element to the uncertainty in the discount rate (e.g., the

cause a smaller reduction of utility for wealthier individuals, either in the future or in current generations. The parameter ρ measures the *pure rate of time preference*: people's behavior reveals a preference for an increase in utility today versus the future. Consequently, it is standard to place a lower weight on utility in the future.

¹⁹ A benchmark value of 2 is near the middle of the range of values estimated or used by Szpiro (1986), Hall and Jones (2007), Arrow (2007), Dasgupta (2006, 2008), Weitzman (2007, 2009), and Nordhaus (2008). However, Chetty (2006) shows that existing evidence of the effects of wage changes on labor supply imposes a tight upper bound on the curvature of utility over wealth and concludes that the standard expected utility model cannot generate high levels of risk aversion without contradicting established facts about labor supply. Recent work also has jointly estimated the components of the Ramsey equation (Evans and Sezer 2005; Anthoff, et al. 2009b).

rate follows a random walk), then it will result in an effective (or certainty-equivalent) discount rate that declines over time. Consequently, lower discount rates tend to dominate over the very long term (see Weitzman 1998, 1999).

The proper way to model discount rate uncertainty remains an active area of research. Newell and Pizer (2003) employ a model of how long-term interest rates change over time to forecast future discount rates. Their model incorporates some of the basic features of how interest rates move over time, and its parameters are estimated based on historical observations of long-term rates. Subsequent work on this topic, notably Groom et al. (2006), uses more general models of interest rate dynamics to allow for better forecasts. Specifically, the volatility of interest rates depends on whether rates are currently low or high and variation in the level of persistence over time. A key question that has emerged but not yet been resolved is the trade-off between potential time inconsistency in choices from allowing for uncertainty in the discount rate and giving greater weight to far future outcomes (Heal 2009).

The Discount Rates Selected for Estimating the SCC

The interagency group drew on both descriptive and prescriptive approaches but relied primarily on the descriptive approach to inform the choice of discount rate. With recognition of its limitations, the interagency group felt that this approach was the most defensible and transparent given its consistency with the standard contemporary theoretical foundations of benefit-cost analysis. The logic of this framework also suggests that market rates should be used for discounting future consumption-equivalent damages. Regardless of the theoretical approach used to derive the appropriate discount rate(s), it is important to note the inherent conceptual and practical difficulties of adequately capturing consumption trade-offs over many decades or even centuries.

In light of disagreement in the literature on the appropriate market interest rate to use in this context and uncertainty about how interest rates may change over time, the interagency group used three certainty-equivalent constant discount rates to span a plausible range of discount rates: 2.5, 3, and 5 percent per year.

The central value, 3 percent, is consistent with estimates provided in the economics literature and the U.S. government's Office of Management and Budget's (OMB) Circular A-4 guidance (OMB 2003) for the consumption rate of interest. Further, 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. Additionally, 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 incorporate the concern that interest rates are highly uncertain over time. It represents the average of the certainty-equivalent rates from the mean-reverting and random walk approaches from Newell and Pizer (2003) starting at a discount rate of 3 percent.²¹ Further, a rate below the riskless rate would be justified if climate investments are negatively correlated with the overall market rate of return. Finally, the use of this lower value is consistent with certain judgments about the prescriptive or normative approach, as well as being more in line with ethical objections that have been raised about higher discount rates due to assumptions about positive values of ρ (e.g. Stern et al. 2006; Stern 2008; Sterner and Persson 2008; Heal 2009).

4. Global or Domestic SCC

An important question in setting the SCC is whether to include damages that are projected to occur outside the United States. Under current federal guidance (OMB 2003), analysis of economically significant proposed and final regulations from the domestic perspective is required, while analysis from the international perspective is optional. With a 2.5 or 3 percent discount rate, the U.S. benefit is about 7-10 percent of the global benefit, on average, across the scenarios analyzed. Alternatively, if the fraction of GDP lost due to climate change is assumed to be similar across countries, the domestic benefit would be proportional to the U.S. share of global GDP, which is currently about 23 percent.

The interagency group concluded that a global measure of the benefits from reducing U.S. emissions is preferable because the climate change problem is highly unusual in at least two respects. First, it involves a global externality: Emissions of most greenhouse gases contribute to damages around the world even when they are emitted in the United States. Consequently, to address the global nature of the problem, the SCC should incorporate the full (global) damages caused by GHG emissions. Second, climate change presents a problem that the United States alone cannot solve. Even if the United States were to reduce its greenhouse gas emissions to zero, that step would be far from enough to avoid substantial climate change. Other countries

²⁰ As a measure of the post-tax 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 2003-2006 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 post-tax risky rate for investments whose returns are positively correlated with overall equity market returns can be obtained by adjusting pre-tax rates of household returns to risky investments (approximately 7 percent) for taxes, yielding a real rate of roughly 5 percent.

²¹ Calculations done by William Pizer using the original simulation program from Newell and Pizer (2003).

would also need to take action to reduce emissions if significant changes in the global climate are to be avoided.

5. Utility Functions and Equity Weighting

A final modeling question 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. 2009a). A per-capita loss of \$500 in GDP, for instance, is weighted more heavily in a country with a per-capita GDP of \$2,000 than in one with a per-capita GDP of \$40,000. In standard economics terms, this would be consistent with a declining marginal utility of income.

Ultimately, the interagency group concluded that this approach would not be appropriate for estimating a SCC value used in domestic regulatory analysis due to both practical and theoretical problems. First, it would require the development of a global utility function. Second, emissions reductions also impose costs, and hence a full accounting would have to consider that a given cost of emissions reductions imposes a greater utility or welfare loss on a poor nation than on a wealthy one.²² Finally, the use of equity weighting directly in benefit-cost analysis, as opposed to conducting a separate distributional analysis, would be a departure from standard operating procedures for the United States Government.

III. Calculating and Selecting SCC Values

Although there is a wide variety of SCC values in the published literature from each of these models, the group's goal of developing SCC estimates based on a consistent set of assumptions could not be met by relying on this literature. Instead, the group obtained access to the three integrated assessments models (FUND, DICE, and PAGE) and ran each of them with the common set of modeling assumptions outlined in the previous section:

- A Roe and Baker distribution for the climate sensitivity parameter bounded between 0 and 10 with a median of 3 °C and a cumulative probability between 2 and 4.5 °C of two-thirds;
- Five sets of GDP, population and carbon emissions trajectories based on the selected EMF-22 scenarios; and
- Constant annual discount rates of 2.5, 3, and 5 percent.

²² Indeed, the use of equity weighting for global differences in costs and benefits would greatly complicate a global trading system for pollution permits under a cap and trade regime.

Because the climate sensitivity parameter is modeled probabilistically, and because PAGE and FUND incorporate uncertainty in other model parameters, the final output from each model run is a distribution over the SCC in year t .

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

1. Input the path of emissions, GDP, and population²³ and calculate the year by year paths of temperature and per capita consumption associated with the baseline path of emissions.
2. Add an additional unit of carbon emissions in year t and recalculate the year by year paths of temperature and per capita consumption in all years beyond t resulting from this adjusted path of emissions.
3. Compute the marginal damages in each year as the difference between the per capita consumption computed in step 1 and step 2.²⁴
4. Discount the resulting path of marginal damages back to the year of emissions using the fixed discount rates and calculate the SCC as the net present value of the discounted path of damages.

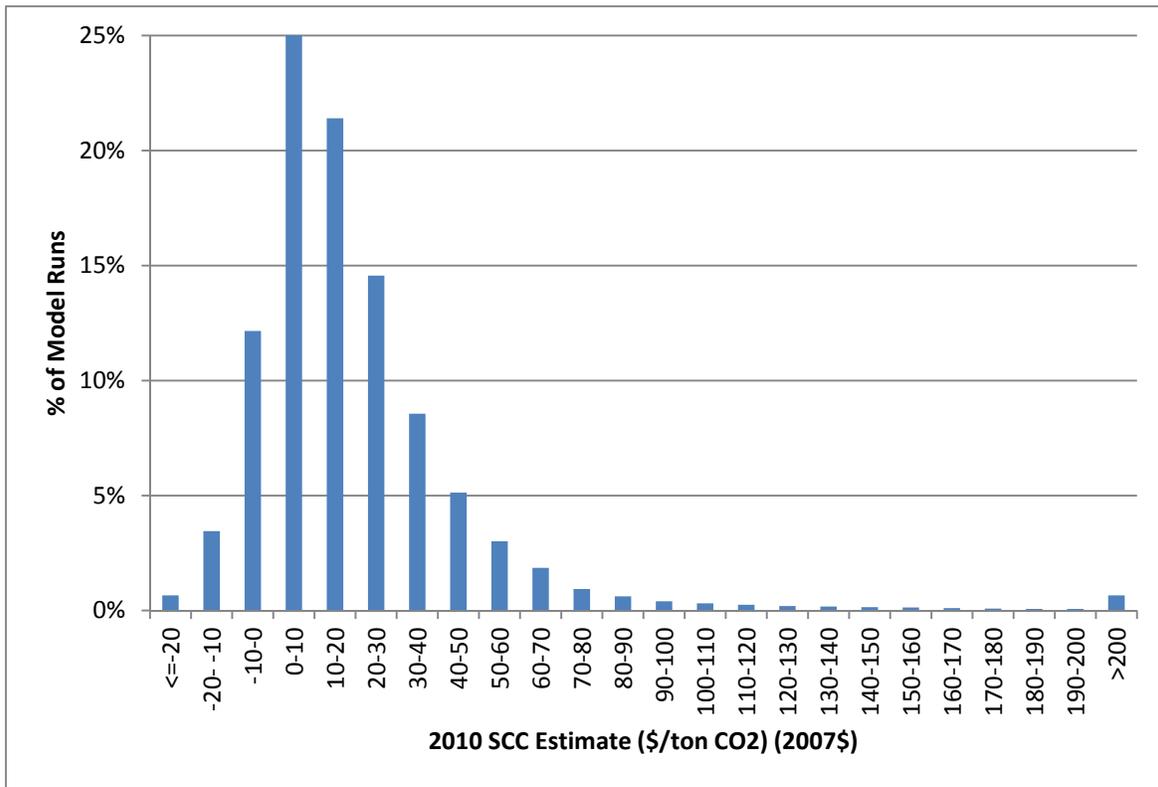
The steps above were repeated in each model for multiple future years to cover the time horizons anticipated for upcoming rulemaking analysis. Because the climate sensitivity parameter is modeled probabilistically, and because PAGE and FUND incorporate uncertainty in other model parameters, the final output from each model run is a distribution over the SCC in year t . Therefore, this exercise produced 45 separate distributions of the SCC for a given year, the product of 3 models, 3 discount rates, and 5 socioeconomic scenarios, clearly too many separate distributions to inform policy decision-making.

²³ To run each model through 2300 requires assumptions about GDP, population, greenhouse gas 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 (CO₂/GDP) growth rate over 2090-2100 is maintained from 2100 through 2300; (4) net land use CO₂ emissions decline linearly, reaching zero in the year 2200; and (5) non-CO₂ radiative forcing remains constant after 2100.

²⁴ DICE is run in 10 year time steps, FUND in annual time steps, while the time steps in PAGE vary.

To produce a range of plausible estimates that still reflects the uncertainty in the estimation exercise, the distributions from each of the models and scenarios are equally weighed and combined to produce three separate probability distributions for SCC in a given year, one for each assumed discount rate. For example, Figure 3 reports on the distribution of 2010 SCC values associated with a 3% discount rate from 150,000 model runs; each of the 15 model-socioeconomic scenario pairs is run a total of 10,000 times to adequately sample the distribution of equilibrium climate sensitivities. The 5th, 25th, 50th, 75th, and 95th percentile values are -\$9, \$4, \$14, \$28, and \$65, respectively.

Figure 3. Histogram of Global SCC Estimates in 2010 (2007\$/ton CO₂), 3% discount rate



Source: DICE, PAGE, and FUND model runs used to generate interagency SCC values.

These distributions are then used to define a range of point estimates for the global SCC. In this way, no IAM or socioeconomic scenario is given greater weight than another. Because the literature shows that the SCC is quite sensitive to assumptions about the discount rate, and because no consensus exists on the appropriate rate to use in an intergenerational context, the interagency group chose to present SCCs based on the average values across models and socioeconomic scenarios for each discount rate.

The interagency group selected four SCC values for use in regulatory analyses. Three values are based on the mean SCC across models and socio-economic and emissions scenarios at the 2.5, 3, and 5 percent discount rates. The fourth value was included to represent the higher-than-expected economic impacts from climate change further out in the tails of the SCC distribution. For this purpose, the group selected the SCC value for the 95th percentile at a 3 percent discount rate. The central value is the average SCC across models at the 3 percent discount rate. For purposes of capturing the uncertainties involved in regulatory impact analysis, the group emphasized the importance and value of considering the full range.

Before examining the specific results, it is important to recall two features of these models. First, catastrophic impacts are incorporated into the SCC values through consideration of their effects in the PAGE and DICE models, as well as the use of a probability density function for equilibrium climate sensitivity. Treating climate sensitivity probabilistically results in more high temperature outcomes, which in turn lead to higher projections of damages. Although FUND does not include catastrophic damages, its probabilistic treatment of the equilibrium climate sensitivity parameter will directly affect the non-catastrophic damages that are a function of the rate of temperature change. Second, the three models vary widely in how they account for compensatory adjustments or adaptation in response to climate change that mitigates its impact on wellbeing. FUND allows for induced adaptation in certain sectors; PAGE assumes adaptation reduces climate impacts but it is exogenously imposed. DICE does not assume any additional adaptation beyond what is included in the studies used to calibrate the damage function.

Table 3 presents SCC estimates for 2010 by model, scenario, and discount rate to illustrate the variability in the SCC across these input parameters. Higher discount rates naturally result in lower SCC values (and vice versa) for each socioeconomic trajectory. It is evident that there are differences in the SCC estimated across the three main models. FUND produces the lowest estimates, while PAGE generally produces the highest estimates. These results are qualitatively similar to the published SCC values based on the latest versions of each model, although those values do not rely on the same set of assumptions.²⁵

²⁵ For example, the interagency group calculated that FUND yields 2010 SCC estimates (in 2007 dollars) at or near zero for a 5 percent discount rate and around \$9 per ton for a 3 percent discount rate; DICE produces a SCC of around \$9 per ton for a 5 percent discount rate (based on Nordhaus 2008); and PAGE yields a SCC close to \$8 per ton for a 4 percent discount rate (based on Hope 2006, 2008). These comparisons are only approximate since the literature generally relies on Ramsey discounting, while constant discount rates are used here.

Table 3: Social Cost of CO₂ Estimates by Model, Socio-Economic Trajectory, and Discount Rate for 2010 (in 2007 dollars)

Model	Socioeconomic reference scenario	Discount rate:			
		5% Mean	3% Mean	2.5% Mean	3% 95th Percentile
DICE	IMAGE	10.8	35.8	54.2	70.8
	MERGE	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	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	-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.

* Descriptions of the socioeconomic scenarios are available through Stanford’s Energy Modeling Forum (EMF):

http://emf.stanford.edu/events/emf_briefing_on_climate_policy_scenarios_us_domestic_and_international_policy_architectures/. Over 2000-2100, the assumed annualized percentage change in CO₂ emissions is 0.8%, 1.6%, 0.5%, 1.1%, and -0.7% for IMAGE, MERGE, MESSAGE, MiniCAM, and the 550 scenario, respectively. The assumed annualized percentage change in per capita GDP is 1.9%, 1.5%, 1.7%, 2.0%, 1.8% for IMAGE, MERGE, MESSAGE, MiniCAM, and the 550 ppm scenario, respectively. The assumed annualized percentage change in population is 0.4% for IMAGE, MiniCAM, and the 550 ppm scenario, and 0.5% for MERGE and MESSAGE.

**Average of the GDP, population, and emission trajectories implied by the IMAGE, MERGE Optimistic, MESSAGE, and MiniCAM models under the 550 ppm CO₂-e full participation, not to exceed, stabilization scenario considered by EMF-22.

The SCC estimates from FUND are sensitive to differences in emissions paths but relatively insensitive to differences in GDP paths across scenarios, while the reverse is true for DICE and

PAGE. This likely occurs because of several structural differences among the models. Specifically in DICE and PAGE, the fraction of economic output lost due to climate damages increases with the level of temperature alone, whereas in FUND the fractional loss also increases with the rate of temperature change. Furthermore, in FUND increases in income over time decrease vulnerability to climate change (a form of adaptation), whereas this does not occur in DICE and PAGE.

Table 4 shows the four selected SCC values in five-year increments from 2010 to 2050. The values for 2010, 2020, 2040, and 2050 are calculated by first combining all outputs (10,000 estimates per model run) from all scenarios and models for a given discount rate in these years. Values for the years in between are calculated using a simple linear interpolation. 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. This approach allows for the calculation of the growth rate of the SCC to be estimated directly using DICE, PAGE, and FUND. This helps to ensure that the estimates are internally consistent with other modeling assumptions.

Table 4: Social Cost of CO₂, 2010 – 2050 (in 2007 dollars)

Discount Rate	5%	3%	2.5%	3%
Year	Avg	Avg	Avg	95th
2010	4.7	21.4	35.1	64.9
2015	5.7	23.8	38.4	72.8
2020	6.8	26.3	41.7	80.7
2025	8.2	29.6	45.9	90.4
2030	9.7	32.8	50.0	100.0
2035	11.2	36.0	54.2	109.7
2040	12.7	39.2	58.4	119.3
2045	14.2	42.1	61.7	127.8
2050	15.7	44.9	65.0	136.2
Annualized % Change, 2010-2050	3.1%	1.9%	1.6%	1.9%

Source: Table 4, Interagency report, modified.

IV. The Social Cost of Carbon in Action

Benefit-cost analysis is an important tool for assessing policies affecting CO₂ and other greenhouse gas emissions but it is not possible without a value for the social cost of carbon. The SCC provides a tool to monetize or summarize the economic value of the climate change induced alterations in human health, ecosystems, agriculture and other facets of life on Earth that

result from a marginal change in CO₂ emissions. It therefore allows for a comparison of the costs associated with policies that reduce CO₂ emissions and the benefits in terms of avoided climate change. The result is that it is possible to separate the policies or regulations that are on net beneficial for society from those that have costs that exceed their benefits.

The SCC has already taken hold in the evaluation of national policy choices. Since the release of these SCC values, the monetized benefits of CO₂ emission reductions have been included in at least 7 major rules (those with costs or benefits above \$100 million) across three Federal departments and agencies. They are also making their way into testimonies and declarations used in court cases; for example, the SCC was used in a Colorado Public Utility Commission hearing regarding Xcel's plan to retire 900 megawatts of coal-fired generation to comply with state law, and more recently in the DC Circuit Court regarding EPA greenhouse regulations.

Table 5 illustrates the central role that the SCC can play in regulatory decision-making by comparing the upfront technology costs to the stream of social benefits out to 2050 from the recent joint U.S. Department of Transportation (DOT) and Environmental Protection Agency (EPA) greenhouse gas emission and fuel efficiency standards for light-duty vehicles in model years 2012 – 2016. Overall, EPA estimates the upfront technology costs of the light-duty GHG rule to be approximately \$350 billion (2007 dollars). Societal benefits – which account for the impact on energy security, refueling, local air pollutants, accidents, noise, and congestion – are estimated to be \$280 billion before accounting for the impact of the rule on CO₂ emissions. Therefore, without accounting for CO₂ emissions, the proposal would cause nearly \$70 billion more in upfront costs than it would accrue in social benefits.²⁶ Once the value of CO₂ emission reductions is incorporated (using the central SCC value), the regulations are estimated to provide over \$100 billion in net benefits to society.

Table 5: Estimated Upfront Technology Costs and Social Benefits of EPA/DOT GHG Emission Standards for Light-Duty Vehicles, 2010 - 2050 (NPV, 3% discount rate)

	Billions of 2007 dollars
Technology Costs	\$345.9
Social Benefits without SCC	\$277.5
Social Benefits of CO ₂ Reductions (using central SCC value)	\$176.7
Social Benefits - Technology Costs without SCC	-\$68.4
Social Benefits - Technology Costs with SCC	\$108.3

Source: U.S. EPA (2010).

²⁶ For this rulemaking, the DOT and EPA estimated more than \$1.5 trillion in fuel savings through 2050 by assuming that consumers take none of these fuel savings into account at the time of purchase. These dwarf all other cost and benefit categories. We excluded any assessment of private fuel savings, 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. Further, after accounting for the value of CO₂ emissions (using the central SCC value), this rule's benefits exceed its costs without making this assumption about consumer's behavior.

V. Directions for Research

Although the scientific and economic literature upon which the SCC is based continues to evolve, the SCC estimates presented in the previous section are the result of the most rigorous process undertaken to date for determining how Federal agencies should value reductions in CO₂ emissions. Indeed, we believe that in many respects the interagency group was able to incorporate the latest research across the multiple disciplines that are key inputs into determining the SCC. This process represents a step forward in increasing transparency and consistency in benefit–cost analyses of federal regulatory actions and can serve as a model for future revisions of the social cost of carbon estimates to keep pace with the latest research. During the course of the modeling, it became apparent to the interagency group that there are several areas in particular need of additional exploration and research. This section summarizes several of these areas below in the hope that their identification will lead to further original research and ultimately updated and improved estimates of the SCC for regulatory analysis.²⁷

A. Incomplete Treatment of Non-catastrophic Damages

The impacts of climate change are expected to be widespread, diverse, and heterogeneous. In addition, the exact magnitude of these impacts is uncertain because of the inherent complexity of climate processes, the economic behavior of current and future populations, and the rate of technological change and adaptation. Current IAMs do not assign value to all of the important physical, ecological, and economic impacts of climate change recognized in the literature because of lack of precise information on the nature of damages and because the science incorporated into these models understandably lags behind the most recent research.²⁸ The area of quantification and monetization of climate change impacts is one where there is significant room for new research.

B. Incomplete Treatment of Potential Catastrophic Damages

There has been considerable recent discussion of the risk of catastrophic impacts 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 may not capture the economic effects of such climate change-induced “catastrophes” and may therefore lead to underestimates of the SCC (Mastrandrea 2009). In particular, the models’

²⁷ To help motivate and inform this process, EPA and DOE also sponsored a pair of invitational workshops in late 2010 and early 2011. The first workshop focused on conceptual and methodological issues related to integrated assessment modeling and valuing climate change impacts, while the second workshop reviewed research on estimating impacts and valuing damages on a sectoral basis. For more information, see <http://yosemite.epa.gov/ee/epa/eed.nsf/webpages/homepage>.

²⁸ Ocean acidification is one example of a potentially large damage from CO₂ emissions not quantified by any of the three models. Species and wildlife loss is another example that is exceedingly difficult to monetize.

functional forms may not adequately capture three categories of losses that many consider catastrophic:

- (1) potentially discontinuous “tipping point” behavior in Earth systems;
- (2) inter-sectoral and inter-regional interactions, including global security impacts of high-end warming; and
- (3) limited near-term substitutability between damage to natural systems and increased consumption.

(1) *Tipping points.* The damage functions in these IAMs are typically calibrated by estimating damages at moderate temperature increases (e.g., DICE is calibrated at 2.5 °C) and extrapolated to far higher temperatures by assuming that damages increase as some power of the temperature change. 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., Lenton et al, 2008, Kriegler et al., 2009). Many of these tipping points are estimated to have thresholds between about 3 °C and 5 °C (Lenton et al., 2008).²⁹

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, Nordhaus (2009) concluded that the conditions under which Weitzman's results hold “are limited and do not apply to a wide range of potential uncertain scenarios.” Using a simplified IAM, Newbold and Daigneault (2009) confirmed that the aggregate benefit estimates can be highly sensitive to the shapes of both the climate sensitivity distribution and the damage function at high temperature changes. Pindyck (2009) also used a simplified IAM to examine high-impact low-probability risks and found only a modest risk premium. 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.

(2) *Failure to incorporate inter-sectoral and inter-regional interactions.* The damage functions do not fully incorporate either inter-sectoral or inter-regional interactions. For instance while

²⁹ Probabilities of several of these tipping points were assessed through expert elicitation in 2005–2006 by Kriegler et al. (2009). 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 across which some aspect of the Earth 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 with high economic impact.

damages to the agricultural sector are incorporated, the effects of changes in food supply on human health are not fully captured and depend on the modeler's choice of studies used to calibrate the IAM. Likewise, the effects of climate damages in one region of the world on another region are not included in some of the models. These inter-regional interactions, though difficult to quantify, are the basis for climate-induced national and economic security concerns (e.g., Campbell et al., 2007; U.S. Department of Defense 2010) and are more likely at higher levels of warming.

(3) *Imperfect substitutability of environmental amenities.* The three IAMs used here assume that it is possible to compensate for the economic consequences of damages to natural systems through increased consumption of non-climate goods, a common assumption in many economic models. In the context of climate change, however, it is possible that the damages to natural systems could become so great that no increase in consumption of non-climate goods would provide complete compensation (Levy et al., 2005; Sterner and Persson 2008). For instance, as water supplies become scarcer or ecosystems become more fragile and less bio-diverse, the services they provide may become increasingly more costly to replace.

C. Incomplete Treatment of Adaptation and Technological Change

Each of the three IAMs used here assumes a certain degree of adaptation. For instance, the largest single benefit category from greenhouse gas mitigation in FUND is the lower electricity costs from reduced air conditioning usage (NRC 2009).

Climate change also will increase returns on investment to develop technologies that allow individuals to cope with adverse climate conditions. IAMs do not adequately account for this directed technological change.³⁰ For example, scientists may develop crops that are better able to withstand higher and more variable temperatures. Although DICE and FUND have both 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. On the other hand, the calibrations also do not account for increases in climate variability, pests, or diseases, which could make adaptation more difficult than assumed by the IAMs for a given temperature change. In this respect, it is difficult to determine whether the incomplete treatment of adaptation and technological change in these IAMs under or overstate the likely damages.

D. Risk Aversion

A key question unanswered during the interagency process is what to assume about relative risk aversion with regard to high-impact outcomes. The group's calculations do not take into account

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.

the possibility that individuals may have a higher willingness to pay to reduce the likelihood of low-probability, high-impact damages than they do to reduce the likelihood of higher-probability but lower-impact damages with the same expected cost. (Indeed, the inclusion of the 95th percentile estimate in the final set of SCC values was largely motivated by this concern.) Using FUND, Anthoff et al (2009) explored the sensitivity of the SCC to Ramsey equation parameter assumptions based on observed behavior. They conclude that “the assumed rate of risk aversion is at least as important as the assumed rate of time preference in determining the social cost of carbon.” The need for further research in this area was recognized by Nordhaus (2008) who pointed to the need to explore the relationship between risk and income in the context of climate change across models and to explore the role of uncertainty regarding various parameters in the results. Interestingly, currently federal policy is to assume risk neutrality.³¹

VI. Conclusion

This paper summarizes the methodology and process used by a U.S. government interagency group to develop SCC values for estimating the incremental benefits of CO₂ reductions associated with regulatory actions. It also discusses key limitations to this analysis with the hope that researchers may help to more adequately address them. Research and modeling improvements are needed so that the SCC estimates used for regulatory analysis by the Federal government can continue to evolve and reflect increasing knowledge of the science and economics of climate impacts. Key areas for future research include improvements in how integrated assessment models capture catastrophic impacts, more attention to how predicted physical impacts translate into economic damages, and a more complete treatment of behavioral assumptions about adaptation and technological changes induced by changing temperatures. The role of a discount rate in a regulatory analysis context where costs and benefits of a policy are on different time horizons requires additional attention and debate as well. Finally, most of the literature focuses on generating a social cost of carbon emissions, but a methodology for valuing reductions in other greenhouse gases is also needed.

³¹ Assuming a risk-neutral representative agent is consistent with Circular A-4 (OMB 2003), which advises that the estimates of benefits and costs used in regulatory analysis are usually based on the average or the expected value and that “emphasis on these expected values is appropriate as long as society is ‘risk neutral’ with respect to the regulatory alternatives. While this may not always be the case, [analysts] should in general assume ‘risk neutrality’ in [their] analysis.”

References

Anthoff D, C. Hepburn, and R. Tol. 2009a. "Equity Weighting and the Marginal Damage Costs of Climate Change." *Ecological Economics* 68:836-849.

Anthoff, D., R. Tol, and G. Yohe. 2009b. "Risk aversion, time preference, and the social cost of carbon." *Environmental Research Letters* 4: 024002 (7pp).

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

Arrow, K.J., et al. 1996. "Intertemporal equity, discounting and economic efficiency," in *Climate Change 1995: Economic and Social Dimensions of Climate Change*, Contribution of Working Group III to the *Second Assessment Report of the Intergovernmental Panel on Climate Change*.

Becker, Gary S., Kevin M. Murphy, and Robert H. Topel. 2011. "On the Economics of Climate Policy." Mimeograph.

Campbell, K. et al. 2007. *The age of consequences: The foreign policy and national security implications of global climate change*. Center for Strategic & International Studies, 119 pp.

Chetty, R. 2006. "A New Method of Estimating Risk Aversion." *American Economic Review* 96(5): 1821–1834.

Dasgupta P. 2006. "Comments on the Stern Review's economics of climate change." University of Cambridge working paper.

Dasgupta P. 2008. "Discounting climate change." *Journal of Risk and Uncertainty* 37:141-169.

Deschenes and Greenstone (forthcoming). "Climate Change, Mortality, and Adaptation: Evidence from Annual Fluctuations in Weather in the US," *American Economic Journal: Applied Economics*, Forthcoming.

Evans D., and H. Sezer. 2005. "Social discount rates for member countries of the European Union." *J. Econ. Stud.* 32 47–59.

Groom, B., Koundouri, P., Panipoulou, E., Pantelidis, T. 2006. "An econometric approach to estimating long-run discount rates." *Journal of Applied Econometrics*.

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." *Phil. Trans. Roy. Soc. A* 365: 1925-1954.
- 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. "Constraints on climate sensitivity from temperature reconstructions of the past seven centuries." *Nature* 440.
- Hope C. 2006. "The marginal impact of CO₂ from PAGE2002: an integrated assessment model incorporating the IPCC's five reasons for concern." *The Integrated Assessment Journal* 6(1):19-56.
- Hope C. 2008. "Optimal carbon emissions and the social cost of carbon under uncertainty." *The Integrated Assessment Journal* 8(1):107-122.
- Interagency Working Group on Social Cost of Carbon. 2010. *Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866*. February. United States Government. <http://www.whitehouse.gov/sites/default/files/omb/inforeg/for-agencies/Social-Cost-of-Carbon-for-RIA.pdf>.
- Intergovernmental Panel on Climate Change. 2007. "Summary for Policymakers." In *Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.
- Just, R., D. Hueth, and A. Schmitz. 2004. *The Welfare Economics of Public Policy*. Glos UK: Edward Elgar Publishing Limited.
- Kriegler, E. et al. 2009. "Imprecise probability assessment of tipping points in the climate system." *Proc. Natl. Acad. Sci.* 106: 5041-5046.
- Le Treut H., et al. 2007. "Historical Overview of Climate Change." in Solomon et al., *Climate Change 2007*.
- Lenton, T., et al. 2008. "Tipping elements in the Earth's climate system." *Proc. Natl. Acad. Sci.* 105: 1786-1793.
- Levy, M., et al. 2005. "Ecosystem conditions and human well-being." In: *Ecosystems and Human Well-being: Current State and Trends, Volume 1*. [R. Hassan, R. Scholes, and N. Ash, eds.] Washington: Island Press. pp. 123-164.

Mastrandrea, M. 2009. "Calculating the benefits of climate policy: Examining the assumptions of Integrated Assessment Models." Pew Center on Global Climate Change Working Paper, 60 pp.

Meehl, G, et al. 2007. "Global Climate Projections." in Solomon et al., *Climate Change 2007*.

National Research Council (NRC) 2009. *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use*. National Academies Press.

Newbold S, Daigneault A. 2009. "Climate response uncertainty and the benefits of greenhouse gas emissions reductions." *Environmental and Resource Economics* 44:351-377.

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.

Nordhaus, W. 2009. "An Analysis of the Dismal Theorem. Cowles Foundation Discussion Paper. No. 1686. January.

Nordhaus W., and Boyer J. 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 17.

Pindyck, R. 2009. "Uncertain Outcomes and Climate Change Policy." NBER Working Paper, No. 15259. August.

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* 318:629-632.

Stern, N., et al. 2006. *Stern Review: The Economics of Climate Change*, HM Treasury, London.

Stern N. 2008. "The economics of climate change." *American Economic Review* 98(2):1-37.

Stern, 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." *The Review of Economics and Statistics* 68(1): 156-9.

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* 21:135-160.

Tol, R. 2009. "An analysis of mitigation as a response to climate change." Copenhagen Consensus on Climate. Discussion Paper.

U.S. Department of Defense. 2010. Quadrennial Defense Review Report. February.

U.S. Environmental Protection Agency. 2010. 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>.

Weitzman, M. 2009. "On modeling and interpreting the economics of catastrophic climate change." *Review of Economics and Statistics* 91:1-19.

Weitzman, M. 2007. "The Stern Review of the Economics of Climate Change." *Journal of Economic Literature* 45, 3:703-724.

Weitzman, M. 1999. In Portney P.R. and Weyant J.P. (eds.), *Discounting and Intergenerational Equity*, Resources for the Future, Washington, D.C.

Weitzman, M. 1998. "Why the Far-Distant Future Should Be Discounted at Its Lowest Possible Rate." *Journal of Environmental Economics and Management* 36 (3): 201-208.