Climate Risks and Carbon Prices: Revising the Social Cost of Carbon

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Abstract The social cost of carbon – or marginal damage caused by an additional ton of carbon dioxide emissions – has been estimated by a U.S. government working group at $21/tCO_2$ in 2010. That calculation, however, omits many of the biggest risks associated with climate change, and downplays the impact of current emissions on future generations. Our reanalysis explores the effects of uncertainty about climate sensitivity, the shape of the damage function, and the discount rate. We show that the social cost of carbon is uncertain across a broad range, and could be much higher than $21/tCO_2$. In our case combining high climate sensitivity, high damages, and a low discount rate, the social cost of carbon could be almost $900/tCO_2$ in 2010, rising to $1,500/tCO_2$ in 2050.

The most ambitious scenarios for eliminating carbon dioxide emissions as rapidly as technologically feasible (reaching zero or negative net global emissions by the end of this century) require spending up to $150 to $500 per ton of reductions of carbon dioxide emissions by 2050. Using a reasonable set of alternative assumptions, therefore, the damages from a ton of carbon dioxide emissions in 2050 could exceed the cost of reducing emissions at the maximum technically feasible rate. Once this is the case, the exact value of the social cost of carbon loses importance: the clear policy prescription is to reduce emissions as rapidly as possible, and cost-effectiveness analysis offers better insights for climate policy than cost-benefit analysis.

1 Introduction

With the U.S. Environmental Protection Agency's recent historic step toward regulation of greenhouse gas emissions, cost-benefit analyses of proposed American regulations can now include an estimate of damages caused by greenhouse gas emissions – or conversely, the benefits of reducing those emissions. It is, however, a very small step: the "social cost of carbon" (SCC), i.e. the damage per metric ton of carbon dioxide (tCO_2), is estimated at \$21 for 2010, in 2007 dollars (Interagency Working Group 2010). Equivalent to \$0.21 per gallon of gasoline,[1] such a low cost seems to suggest that only modest, inexpensive measures are needed to address climate risks.[2]

The analysis by the federal Interagency Working Group is significant for its role in setting U.S. climate policy, and for its recognition that policy should be based on global, rather than domestic, impacts (unlike most national environmental policies). It is also noteworthy as a rare instance where economic theories and analyses have been newly introduced into the public policy debate.[3] Thus it is important to examine the uses of climate economics in the Working Group analysis, particularly the treatment of the crucial uncertainties that characterize the field. This paper presents an examination and re-analysis of the SCC, finding that four major uncertainties in the economics of climate change could imply much larger estimates. In each case, the Working Group has chosen the option that minimizes estimates of climate risks and damages.

We begin with a discussion of the choice of models and scenarios for the SCC calculation. Our re-analysis relies on the Dynamic Integrated model of Climate

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[1] According to the U.S. Environmental Protection Agency, there are 8.8 kg of CO_2 emissions from a gallon of gasoline, implying that 114 gallons of gasoline yield one metric ton of emissions (the standard unit for analysis of emissions); 103 gallons yield one short ton of emissions (see http://www.epa.gov/oms/climate/420f05001.htm, accessed April 22, 2011). Thus a useful rule of thumb is that \$1 per ton of CO_2 is equivalent to roughly \$0.01 per gallon of gasoline. The estimate in the text of \$0.21 per gallon is offered solely for the sake of comparison; there are no existing or proposed federal regulations that would add a carbon charge to the price paid for gasoline.

[2] On the implications of low SCC values, see Ackerman and Stanton (2010).

[3] It is new only for U.S. policy; other countries, notably the United Kingdom, are several years ahead of the United States in this respect. The U.S. policy process is unfortunately parochial, however, so that the introduction of climate economics into American policy analysis is presented with almost no reference to other countries' experience.

and the Economy (DICE), one of the models used in the Interagency Working Group analysis that produced the $21/tCO_2$ estimate. We use the Working Group's modified version of DICE, the same five scenarios on which they based their calculations, and the same framework of Monte Carlo analysis.

We then introduce four major areas of uncertainties that affect the calculation: the sensitivity of the climate to greenhouse gases; the level of damages expected at low temperatures; the level of damages expected at high temperatures; and the discount rate. We recalculate the SCC based on combinations of high and low alternatives for each of these factors, yielding an array of 16 values, both for 2010 and for 2050.

Some of the resultant values for the SCC are extremely high; the highest ones are close to $900/tCO_2$ in 2010 and $1,500 in 2050. In contrast, a review of scenarios that reach zero or negative net global emissions within this century finds that they often imply carbon prices, and marginal abatement costs, of $150 to $500/tCO_2$ by 2050. Many of our alternative SCC values are within or above this range – and still would be, even if recalculated on a low-emissions scenario.

We conclude with a discussion of the meaning of very high SCC estimates. Once the SCC reaches or exceeds the cost of bringing net emissions to zero, its exact value becomes less important; if the SCC were twice as large, it would have the same policy implications. At such high SCC values, cost-benefit analysis of individual policies provides no useful information; what is needed instead is a cost-effectiveness analysis of the least-cost, most efficient pathway to reach zero or negative net emissions.

2   Choice of Models

The Interagency Working Group used three well-known models of climate economics: DICE, Policy Analysis of the Greenhouse Effect (PAGE), and Framework for Uncertainty, Negotiation and Distribution (FUND).[4] They ran each of the models on the same five scenarios, in Monte Carlo mode, examining the effects of a range of values for climate sensitivity and (in PAGE and FUND) many

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[4] For a description of DICE, see Nordhaus (2008); for PAGE, see Hope (2006a); for FUND, see Anthoff and Tol (2009).

other uncertainties. Under their "central case" – the mean value at a 3 percent discount rate – the value of the SCC, averaged across the five scenarios, was $28/tCO$_2$ in DICE, $30 in PAGE, and $6 in FUND, for a three-model average of $21.

Our re-analysis uses only the DICE model, which is the easiest of the three to modify for our purposes. As suggested by the Working Group's central case results, it is likely that FUND would have produced lower estimates than those reported below, while PAGE would have produced higher estimates. Regarding the latter, PAGE has an explicit treatment of potential climate catastrophes, using a Monte Carlo analysis that allows variation in the size of catastrophes, the temperature threshold at which they become possible, and the likelihood of catastrophe once the threshold has been passed. DICE, in contrast, includes the certainty-equivalent or expected value of catastrophe in its damage function. As a result, PAGE estimates a higher SCC than DICE at lower discount rates or higher climate sensitivity.[5] Our analysis includes both lower discount rates and higher climate sensitivity, so our SCC estimates would have been higher if we had used PAGE.

3   Choice of Scenarios

The Working Group analysis rejects the widely used Intergovernmental Panel on Climate Change (IPCC) climate scenarios, and instead uses scenarios from four other models: the business-as-usual scenarios from IMAGE, MERGE, MESSAGE, and MiniCAM, and a 550 ppm stabilization scenario.

It is difficult to interpret the inclusion of the 550 ppm scenario. Does it imply a guess that under business-as-usual conditions, there is a 20-percent chance that the world will reach agreement on stabilization at that level? No explanation is offered. Moreover, the 550 ppm scenario is not even a single, internally consistent scenario; rather, its GDP, population, and emissions trajectories are averages of the

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[5] A lower discount rate increases the importance of events farther in the future, when temperatures are higher and catastrophes are more likely. Higher climate sensitivity makes higher temperatures and increased risks of catastrophe occur sooner. For these reasons, PAGE estimates a larger SCC than DICE at a 2.5-percent discount rate, and at 95th percentile climate sensitivity; see Interagency Working Group on Social Cost of Carbon (2010), Table 3.

values in the 550 ppm scenarios from the other four models (see Interagency Working Group 2010, 16).

Nonetheless, inclusion of the 550 ppm scenario makes little difference in practice. Excluding it would cause only a $1 increase to the $21/tCO$_2$ SCC average estimate from DICE, FUND, and PAGE, or the $28 estimate from DICE alone. For the ensemble of 16 SCC estimates in our analysis, presented below, exclusion of the 550 ppm scenario would cause an average increase of less than 4 percent; all of our estimates would change by less than 17 percent in either direction.

The four business-as-usual scenarios used by the Working Group were adopted from an Energy Modeling Forum (EMF) model comparison exercise (Clarke et al. 2009). For those who are not familiar with EMF, it may be helpful to contrast the selected EMF scenarios with the IPCC's SRES scenarios.[6] Figure 1 and Figure 2 compare the cumulative carbon dioxide emissions and current methane emissions from the four EMF scenarios and tree IPCC scenarios, A2, B2, and B1.[7] As Figure 1 shows, carbon dioxide emissions in the four EMF scenarios (solid lines) are close to the B1 and B2 scenarios for the first half of this century, spreading out to roughly span the interval from A2 to B2 by 2100.

For methane emissions, Figure 2 shows that three of the four EMF scenarios start out well below the level of the B1 and B2 scenarios; by 2100, all four are roughly at or below the level of B2. In short the emissions trajectories of the EMF scenarios are broadly within, but toward the lower end of, the spectrum of IPCC SRES scenarios, perhaps closest to B2.

All else being equal, lower emissions usually imply lower temperatures, lower damages, and therefore a lower estimate of the SCC (for a discussion of countervailing factors see section 7). Use of a scenario in which emissions grow more rapidly, such as A2, would likely have led to higher values for the SCC.

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[6] IPCC scenario data are from http://sres.ciesin.org/final_data.html , downloaded March 1, 2011. EMF scenario data are from
http://emf.stanford.edu/events/emf_briefing_on_climate_policy_scenarios_us_domestic_and_internat ional_policy_architectures , downloaded February 15, 2011.
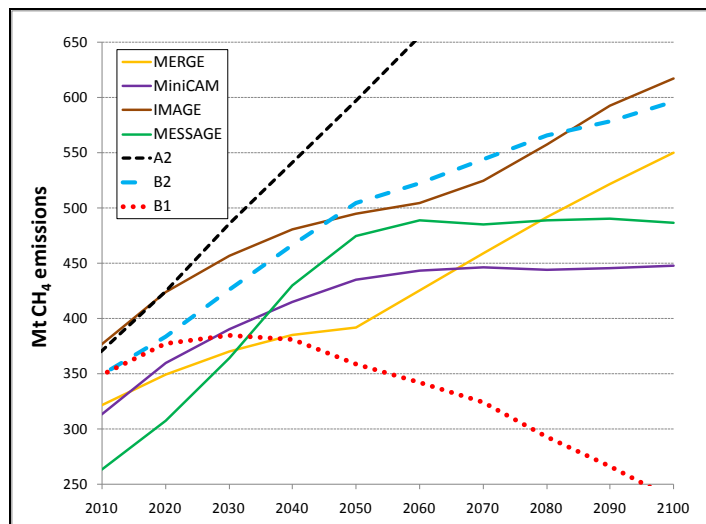
[7] Figure 1 presents cumulative emissions because CO_2 persists in the atmosphere for long periods of time; Figure 2 presents current emissions because methane is removed from the atmosphere much more quickly.

Figure 1: Comparing EMF and IPCC CO₂ emission scenarios
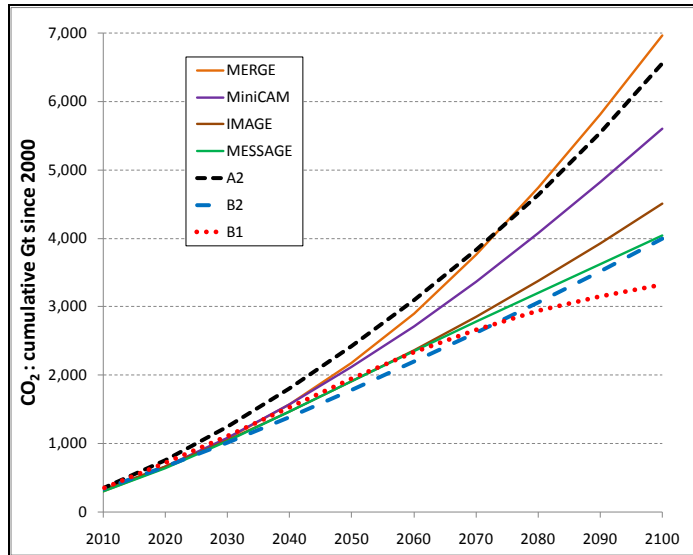
Source: See text.

Figure 2: Comparing EMF and IPCC CH₄ emission scenarios

Source: See text.

For the sake of comparability with the Working Group results, we have adopted the same five scenarios in our analysis of uncertainties. Kopp and Mignone (2011) provide a more detailed evaluation of the Working Group's emission scenarios as part of a discussion of the full set of assumptions used in the Working Group's analysis.

4 Four Uncertainties

This section explores four major uncertainties that affect the SCC calculation: the value of the climate sensitivity parameter; the level of climate damages expected at low temperatures; the level of damages at high temperatures; and the discount rate. Section 5 presents multiple estimates of the SCC, based on alternatives for each of these uncertainties.

4.1 Climate Sensitivity

The climate sensitivity parameter is the long-term temperature increase expected from a doubling of the concentration of carbon dioxide in the atmosphere. This crucial parameter, which measures the pace of global warming, remains uncertain, and there are reasons to believe that significant uncertainty about climate sensitivity is inescapable (Roe and Baker 2007).

On this topic, the Working Group analysis is impressively thorough. They discuss the scientific evidence on likely values of climate sensitivity, and adopt a probability distribution which assumes a two-thirds probability that climate sensitivity is between 2.0°C and 4.5°C. The minimum is zero and the maximum is 10°C; the distribution has a median of 3.0°C and a 95th percentile of 7.14°C. They then perform a Monte Carlo analysis, repeatedly selecting a climate sensitivity value from this probability distribution. In PAGE and FUND, there are numerous other Monte Carlo variables, representing other uncertainties; in DICE, normally a deterministic model, climate sensitivity is the only Monte Carlo variable in the Working Group analysis.

The Working Group reports, but does not emphasize, the 95th percentile results. For DICE in particular, those results are a measure of the potential impact

of uncertainty about climate sensitivity. Results for DICE, and for the three-model average used by the Working Group, are presented in Table 1.

We follow the Working Group in calculating average and 95th percentile SCC results over 10,000 iterations, using the same probability distribution for climate sensitivity as the Working Group, in each of the five climate scenarios for each of the variations described below. In DICE, the average and 95th percentile results may correspond to climate sensitivity somewhat below 3.0°C and 7.14°C, respectively, since actual climate sensitivity in DICE (and several other integrated assessment models) is lower than the reported values. DICE uses a default climate sensitivity of 3.0°C, but actually responds to a doubling of atmospheric carbon dioxide with a long-run temperature increase of 2.77°C (van Vuuren, Lowe, et al. 2011).

Table 1: SCC estimates, 2010 and 2050, 3% discount rate

Emissions year	Result	DICE	3-Model Average
2010	Average	$28	$21
2010	95th percentile	$56	$65
2050	Average	$64	$45
2050	95th percentile	$123	$136

Source: Interagency Working Group (2010). For DICE, average and 95th percentile results are based on the probability distribution for climate sensitivity. For PAGE and FUND, the corresponding results refer to the entire Monte Carlo analysis, including uncertainty about other parameters as well as climate sensitivity.

4.2   Damage Function Estimates

Like climate sensitivity, the relationship between temperature increases and economic damage is uncertain. The Working Group says little about the estimates of economic damages from climate change, except to call for additional research. Kopp et al. (2011) modify the Working Group's version of the DICE model by including uncertainty in the damage function and varying the level of risk aversion

in the discount rate. We take a simpler approach: the damage function remains a certainty equivalent, but we explore alternative functional forms and parameter values.

DICE assumes that as temperatures rise, an increasing fraction of output is lost to climate damages. We will use D for damages as a fraction of the GDP that would be produced in the absence of climate change; $R = 1 - D$ for the net output ratio, or output net of climate damages as a fraction of output in the absence of climate change; and T for global average temperature increase in $^{\circ}$C above 1900. The DICE damage function is:

(1) $R = 1 / (1 + .00284\ T^2)$

Or equivalently,

(2) $R = 1 / [1 + (T / 18.8)^2]$

The DICE net output ratio can be viewed as combining two separate estimates: first, for low temperatures, William Nordhaus, the creator of DICE, estimates that damages are 1.7 percent of output at 2.5°C (Nordhaus 2007); second, at high temperatures, it is assumed by default that the quadratic relationship of damages to temperature in (1) or (2) continues to apply. Separate research addresses the low-temperature and high-temperature estimates, suggesting alternatives to each.

The DICE low-temperature damage estimate is based on an evaluation of several categories of climate damages at 2.5°C (Nordhaus 2008; Nordhaus and Boyer 2000). In a review and critique of the Nordhaus estimates as applied to the United States, Michael Hanemann develops alternative estimates for damages at 2.5°C, which are, in total, 2.4 times the Nordhaus value (Hanemann 2008).[8] If the same relationship applies worldwide, then a reasonable alternative at low

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[8] Hanemann compares his calculations to an earlier version of DICE; Hanemann's estimate is 4.0 times the DICE-99 estimate, or 2.4 times the DICE-07 estimate, of damages at 2.5°C.

temperatures is to keep the form of equation (1) or (2), but recalibrate damages to 4.2 percent of output at $2.5°$C. This yields the equation:

(3) $R = 1 / [1 + (T / 12.0)^2]$

Neither the Nordhaus nor the Hanemann $2.5°$C estimate provides a basis for projecting damages at much higher temperatures.[9] It has become conventional to extrapolate the same quadratic relationship to higher temperatures, but there is no economic or scientific basis for that convention. The extrapolation implies that damages grow at a leisurely pace, especially in the Nordhaus version: from equations (2) and (3), it is easy to see that half of world output is not lost to climate damages until temperatures reach almost $19°$C according to DICE, or $12°$C in the Hanemann variant.

In a discussion of damage functions and catastrophic risks, Martin Weitzman argues that even if the Nordhaus estimate is appropriate for low-temperature damages, the increasingly ominous scientific evidence about climate risks implies much greater losses at higher temperatures (Weitzman 2010). He suggests that damages should be modeled at 50 percent of output at $6°$C and 99 percent at $12°$C as better representations of the current understanding of climate risks; the latter temperature can be taken as representing the end of modern economic life, if not human life in general. In support of this disastrous projection for $12°$C of warming, Weitzman cites recent research showing that at that temperature, areas where half the world's population now lives would experience conditions, at least once a year, that human physiology cannot tolerate – resulting in death from heat stroke within a few hours (Sherwood and Huber 2010).

Weitzman creates a damage function that matches the DICE estimate at low temperatures, but rises to his suggested values at $6°$C and $12°$C. He modifies (2) by adding a higher power of T to the denominator:[10]

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[9] Nordhaus presents some numerical estimates of damages at $6°$C, suggesting they are between 8 percent and 11 percent of output (Nordhaus 2007); these estimates are not well documented, and do not appear to be used in the calibration of DICE.

[10] This equation follows Weitzman's method but differs slightly from his numerical estimates. He appears to have taken the DICE coefficient in (1) to be .00239 rather than .002839. Our equations (4)

(4) $R = 1 / [1 + (T / 20.2)^2 + (T / 6.08)^{6.76}]$

When T is small, the quadratic term in (4) is more important, providing a close match to the original DICE damage function; when T is large, the higher-power term is more important, allowing the damage function to match Weitzman's values for higher temperatures.

The same method can be applied to the Hanemann low-temperature estimate in (3); calibrating to Hanemann's value at 2.5°C, and Weitzman's values at 6°C and 12°C, we obtain:

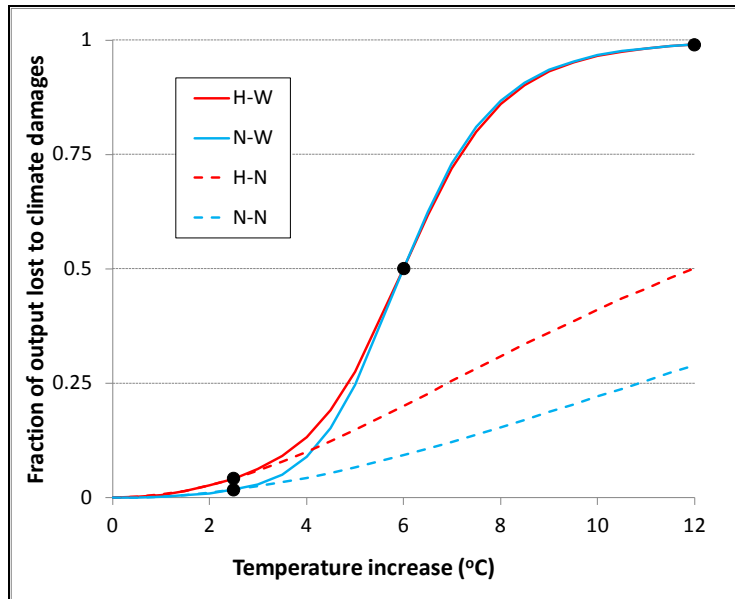(5) $R = 1 / [1 + (T / 12.2)^2 + (T / 6.24)^{7.02}]$

Equations (2), (3), (4), and (5) incorporate all combinations of two low-temperature alternatives (Nordhaus and Hanemann), and two high-temperature alternatives (Nordhaus and Weitzman). Using their initials, these can be labeled as the N-N, H-N, N-W, and H-W damages functions, respectively. They are displayed in Figure 3 (the graph presents damages as a share of GDP, i.e. $D = 1 - R$), with large dots indicating the points used for calibration. Below 3°C, the low-temperature alternatives are dominant, and the high-temperature alternatives make no visible difference; at 6°C and above, the high-temperature alternatives determine the shape of the damage function. In particular, the two damage functions with the Weitzman high-temperature assumption are nearly identical above 6°C.[11]

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and (5) were fitted to minimize the sum of squared deviations from the Nordhaus and Hanemann damage estimates, respectively, at 2.5°C, and the Weitzman point estimates at 6°C and 12°C.

[11] A small anomaly is that between 6°C and 12°C the N-W damage function, despite its lower low-temperature damages, is slightly higher than H-W; the gap is widest at 6.9°C, where N-W damages are 1.5 percent above H-W.

Figure 3: Damages as a share of GDP in four damage functions

4.3   Discount Rates

The Working Group's analysis of the SCC is based on projected costs and benefits extending 300 years into the future, as is our reanalysis. Across such spans of time, the discount rate is crucial to the bottom-line evaluation: the lower the discount rate, the more important the outcomes in later years will be. It seems safe to say that there is ongoing controversy and a lack of consensus on the appropriate discount rate to use in climate economics.

The Working Group discusses the discount rate at length, justifying their choice of a fixed rate of 3 percent. This is one of the discount rates normally recommended for use in U.S. government policy analyses. It can be supported within either of the two frameworks used to determine the discount rate, the descriptive and prescriptive approaches (Arrow et al. 1996). The descriptive approach calls for use of an appropriate market interest rate; the Working Group estimates the real risk-free rate of return, after tax, at 2.7 percent. The prescriptive

approach deduces the discount rate from first principles, as the sum of "pure time preference" (the discount rate that would apply if per capita consumption were constant) plus a multiple of the rate of growth of per capita consumption. The Working Group concludes that "arguments made under the prescriptive approach can be used to justify discount rates between roughly 1.4 and 3.1 percent" (Interagency Working Group 2010, 23), and expresses skepticism about the lower end of that range.

Both descriptive and prescriptive arguments can be made for discount rates below 3 percent. The long-term average risk-free rate is often estimated to be lower than 2.7 percent.[12] In addition, if climate mitigation, like insurance, is most valuable in circumstances that reduce incomes, then the discount rate should be lower than the risk-free rate of return. Using the prescriptive approach, the Stern Review spells out in detail the arguments for a low discount rate, on grounds of intergenerational equity (Stern 2006). Stern's recommended formula for the discount rate is 0.1 percent plus the rate of growth of per capita consumption; this implies an average of 1.4 percent per year, in the Stern Review's model.

To explore the effect of discount rates on the SCC, we use two rates, 3 percent and 1.5 percent per year – approximating the range that the Working Group identified as supportable under the prescriptive approach (as quoted above). Our lower rate is close to the Stern Review's rate; moreover, it is the average rate that would result from applying Stern's formula, 0.1 percent plus the rate of growth of per capita consumption, to the first 200 years of the Working Group's four business-as-usual scenarios.[13]

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[12] Since World War II, real returns have averaged 1.4 percent per year on Treasury bills and 1.1 percent on government bonds (DeLong and Magin 2009).

[13] The EMF scenarios adopted by the Working Group have variable rates of growth by region and time period throughout the scenarios. Using Stern's formula, or any version of the prescriptive approach, this should call for a time-varying, often declining discount rate. We follow the Working Group's practice of using a fixed discount rate, for the sake of comparability with their results and minimization of changes to their version of the DICE model.

5   Results

The previous section identified two alternatives for each of four major factors influencing the SCC:

- Average versus 95th percentile climate sensitivity
- Nordhaus versus Hanemann damage estimates at low temperatures
- Nordhaus versus Weitzman damage estimates at high temperatures
- 3.0 versus 1.5-percent fixed discount rate

We calculated the SCC under each combination of these alternatives, making no other changes to the Working Group's version of DICE.[14] This involved re-running the Monte Carlo analysis, with 10,000 iterations sampling the same probability distribution for climate sensitivity used by the Working Group, for each of the four damage functions shown in Figure 3, the 1.5 and 3.0-percent discount rates, and the five EMF climate scenarios. The results are shown in Figure 4 for 2010, and Figure 5 for 2050. Circles represent average climate sensitivity, and triangles 95th percentile; solid blue symbols represent 1.5-percent discount rates, and outlined orange symbols 3-percent. Results for the four damage functions are shown in four columns on the graphs, as marked.

The SCC is generally higher for later years, since GDP, as well as atmospheric concentrations of greenhouse gases, and temperatures, will be higher at that time – implying that the incremental damage from another ton of carbon dioxide emissions will be greater as well. So it is not surprising that the SCC estimates for 2050 are much higher than the corresponding figures for 2010.

In both graphs, the N-N (original DICE) damage function leads to lower estimates than any of the alternatives. If Hanemann is right about low-temperature damages, then the SCC in 2050 is above $100/tCO$_2$ at a 3-percent discount rate, or about $400 at 1.5 percent. If Weitzman is right about high-temperature damages, the mid-century SCC is above $200 at a 3-percent discount rate, or above $700 at 1.5 percent. At either discount rate, the estimates with Weitzman high-temperature
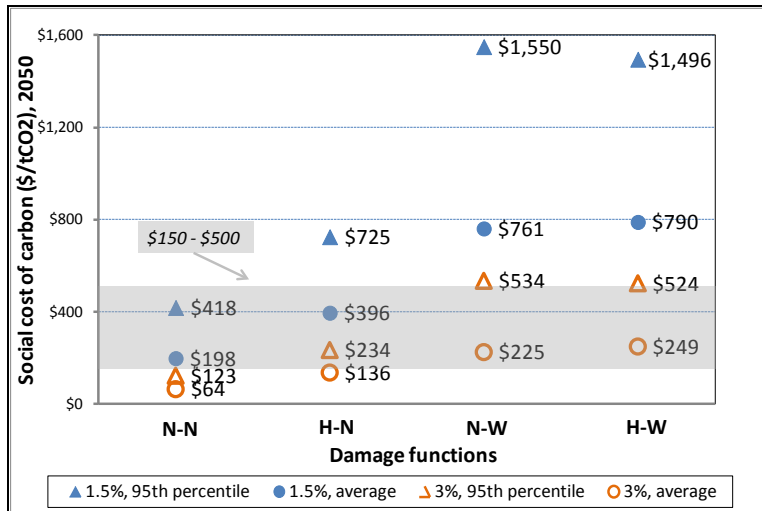
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[14] Thanks to Steve Newbold for making the Working Group's modified version of DICE available for independent analysis. We used the Working Group's DICE code, written in MatLab, with no modifications other than those described in this article.

Figure 4: Estimates of the SCC in 2010
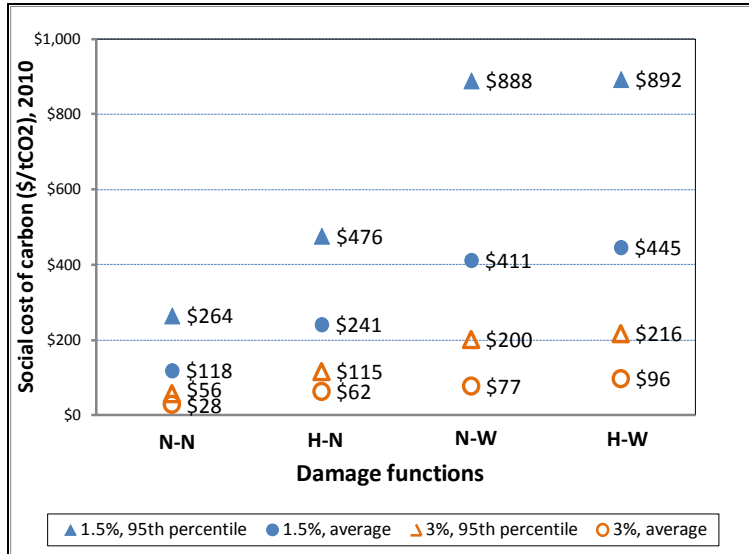
Source: Authors' calculations, in 2007 dollars.

Figure 5: Estimates of the SCC in 2050

Source: Authors' calculations.

damages and 95th percentile climate sensitivity are almost four times higher than the N-N (original DICE) 95th percentile values, and seven to eight times higher than the N-N average values.

6 Abatement Costs

In a cost-benefit analysis of climate policy, the costs of doing nothing about climate change – i.e., the SCC – should be compared to the costs of doing something to mitigate it – i.e., the cost of reducing emissions. In several ambitious scenarios for drastic reduction in global emissions, the marginal cost per ton of abatement is lower than many of the SCC estimates presented above.

An inter-model comparison project, run by researchers at the Postdam Institute for Climate Change Research (PIK) in Germany, compared scenarios from five models that stabilize carbon dioxide concentrations at 400 ppm by 2100.[15] Because carbon dioxide remains in the atmosphere for decades or centuries, and we are already at 390 ppm, these scenarios have to achieve negative net global emissions before 2100, through measures such as reforestation and biomass burning with carbon capture and sequestration (CCS). In general, the 400 ppm scenarios strain the limits of plausible rates of technological and socioeconomic change. Their carbon prices reach $150-$500/tCO_2 by 2050, with an average of $260.[16]

A similar, though slightly more pessimistic, scenario from the International Energy Agency (IEA), stabilizes the atmosphere at 450 ppm of CO_2. This scenario – IEA's "BLUE Map" – again strains the limits of possible technical change, and is meant to represent the maximum feasible pace of abatement. The marginal abatement cost in 2050 is between $175 and $500/t$CO_2$, depending on the degree of technological optimism or pessimism in cost forecasts (IEA 2008; 2010).

A more optimistic variant on this theme, from McKinsey & Company, projects rapid abatement leading to eventual stabilization at 400 ppm CO_2-equivalent;

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[15] See Edenhofer et al. (2010); Kitous et al. (2010); Magne et al. (2010); Leimbach et al. (2010); Barker and Scrieciu (2010); and van Vuuren et al. (2010).

[16] All dollar figures for abatement costs in this section are in 2005 dollars, roughly comparable to our SCC estimates in 2007 dollars; U.S. consumer prices increased 6 percent from 2005 to 2007.

atmospheric concentration peaks at 480 ppm CO_2-e in the 2060s before declining. McKinsey estimates the marginal abatement cost of this scenario at \$90-\$150/tCO_2-e in 2030 (McKinsey & Company 2009).

The British government assigns values to carbon emissions for use in long-term policy appraisals. Its estimates are based on marginal abatement costs under scenarios that are consistent with staying under 2°C of warming – which, in practice, is close to the maximum technically feasible pace of abatement. Their estimated carbon value for 2050 is £200 $\pm$ £100/t CO_2-e (U.K. Department of Energy & Climate Change 2009). At mid-2011 exchange rates, £100-£300 is equivalent to about \$165-\$495.

Comparing these abatement cost estimates to our SCC calculations, the low-stabilization-trajectory scenarios compared by PIK, the IEA BLUE Map, and the UK government carbon values all imply abatement costs of roughly \$150 to \$500/tCO_2 by 2050 – the region shaded in gray in Figure 5. Only three of our 16 SCC estimates for 2050 are below this range; all three assume Nordhaus (lower) high-temperature damages and a 3-percent discount rate. Eight of our estimates are within or barely above this range, and five are well above it. All of the top five assume a 1.5-percent discount rate, and four of the five assume Weitzman high-temperature damages.

The McKinsey estimate of the marginal cost for rapid abatement, \$90-\$150/tCO_2 in 2030, is a range that has already been reached or exceeded by most of our SCC estimates for 2010. Four of the eight estimates for 2010 at a 3-percent discount rate, and all eight of the estimates for 2010 at 1.5 percent, are at or above the McKinsey marginal abatement cost estimate for 2030.

In short, if either low-temperature or high-temperature damages are worse than DICE assumes, then the SCC is roughly at the marginal abatement cost for a maximal abatement scenario at a 3-percent discount rate, or well above that level at a 1.5-percent discount rate. Even with the original DICE damage function, the SCC estimates at a 1.5-percent discount rate are roughly comparable to the marginal cost of a maximal abatement path.

7 Sensitivity Analysis: SCC Estimates with Low Emissions

It would be possible to raise the objection that the comparison presented here is inappropriate: we compare the SCC, estimated on relatively high emissions scenarios, to marginal abatement costs of ambitious mitigation scenarios with much lower emissions. If the SCC were re-estimated on a rapid abatement trajectory, where marginal abatement costs reach \$150 to \$500/tCO_2 by 2050, would the SCC still equal or exceed this range?

To test this possibility, we replaced the CO_2 emissions and non-CO_2 forcings in all five DICE scenarios with the corresponding data for the IPCC's new RCP2.6 scenario (also called RCP3-PD).[17] RCP2.6 is designed to represent the emission reductions required to reach the widely discussed target of keeping temperature increases under 2°C; it projects more than 95 percent reduction in annual emissions of all greenhouse gases by 2100, and implies marginal abatement costs of around \$160 per ton of CO_2 in 2050 (van Vuuren, Stehfest, et al. 2011).

Our use of the RCP2.6 emissions and forcings is a sensitivity analysis, not a complete implementation of the RCP2.6 scenario assumptions. Specifically, we left GDP and population projections unchanged in all five of the Working Group's DICE scenarios, and assumed constant annual emissions and forcings after 2100. Nonetheless, recalculation of our results with RCP2.6 emissions and forcings provides a good test of the sensitivity of SCC estimates to emissions trajectories. The results for 2050 with RCP 2.6 emissions are shown in Figure 6, which can be compared to Figure 5, our 2050 results with the Working Group emissions trajectories.

The estimates with the N-N (original DICE) damage function are relatively little changed; they are only 2 to 14 percent smaller with the drastically lower RCP2.6 emissions, compared to the Working Group scenarios. This is consistent with the findings of Hope (2006b), who demonstrates that the SCC is insensitive to variations in emissions trajectories in the PAGE model. Hope's explanation is that two opposite effects are roughly equal in importance. On the one hand, radiative forcings, and therefore temperatures, are proportional to the logarithm of

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[17] Data downloaded from http://www.iiasa.ac.at/web-apps/tnt/RcpDb , December 2011.

Figure 6: Estimates of the SCC in 2050 with RCP2.6 emissions
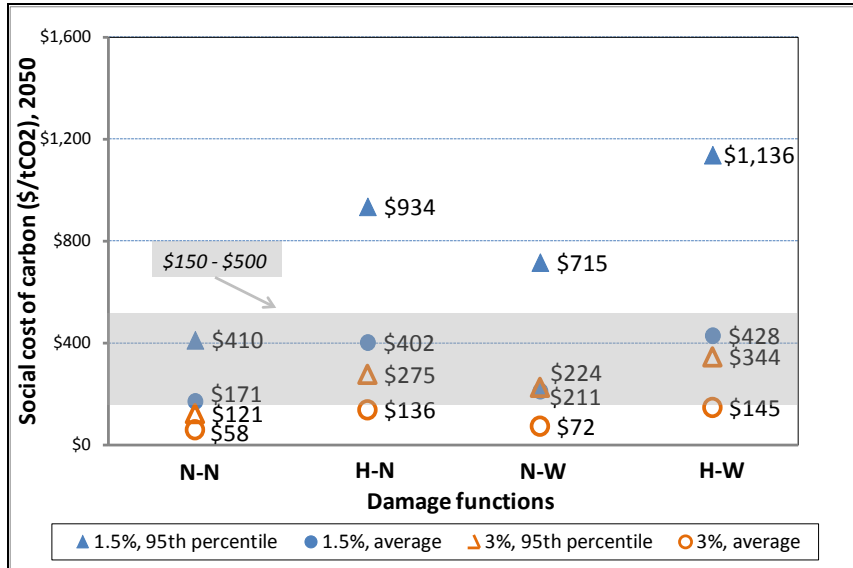
atmospheric concentrations of greenhouse gases; this implies that at lower concentrations, a given increase in emissions causes a greater increase in temperature. On the other hand, damages increase more than linearly with temperature; this implies that at higher concentrations and temperatures, a given increase in temperature causes a greater increase in damages.

While these two effects will always work in opposite directions, the near-equality in their magnitude found by Hope (2006b) appears to depend on the assumed shape of the damage function. Our N-N damage function may be the closest, among our four options, to the PAGE damage function used in that analysis.

Our results with the H-N damage function are, counterintuitively, unchanged or higher with RCP2.6 emissions (Figure 6) than with the Working Group scenarios (Figure 5). This reflects a small anomaly in the data. While RCP2.6 emissions become sharply lower by late in this century, and remain very low thereafter, they do not start out below the Working Group scenarios. Under RCP2.6, CO_2 emissions are close to the average of the five Working Group scenarios for the first three decades; and RCP2.6 non-CO_2 forcings are well above

the Working Group scenario average for the first five decades.[18] The H-N damage function uses our higher assumption about low-temperature damages, which would result from early emissions, but our lower assumption about high-temperature damages, which result primarily from later emissions. Thus its results are the most affected by the initial years when the RCP2.6 trajectory is at or above the Working Group scenario average.

Conversely, the N-W damage function is less sensitive to low-temperature damages and early emissions, but more sensitive to high-temperature damages and later emissions. The RCP2.6 reduction in later emissions has the greatest effect here, with all four N-W SCC estimates in Figure 6 at less than half of the corresponding levels in Figure 5. The H-W damage function is, in this respect, an intermediate case; the H-W SCC estimates are reduced by roughly one-quarter to one-half under RCP2.6, compared to the Working Group emissions.

The bottom line is that even with the rapid emission reductions projected under RCP2.6, our SCC estimates are at or above the estimated marginal abatement cost for a maximal abatement strategy ($150 - $500/$tCO_2$) in 11 of the 16 cases, as seen in Figure 6. The worst cases, involving 95th percentile climate sensitivity, a 1.5-percent discount rate, and any damage function except N-N, are all above $700/$tCO_2$. At the other extreme, the only cases with SCC below $100/$tCO_2$ at mid-century are the two estimates using average climate sensitivity, a 3-percent discount rate, and the Nordhaus estimate of low-temperature damages.

8 Conclusions

We began by reviewing the U.S. government's estimate of the SCC, developed for use in cost-benefit analysis of regulatory proposals. We have ended with alternate estimates that are not just minor revisions to the published figure of $21 per ton, but are higher, in most cases, by an order of magnitude or more. These estimates appear to be well outside the bounds of realistic short-term policy options, in the United States or elsewhere. How should these ultra-high SCC values be interpreted?

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[18] DICE uses an estimate of non-CO_2 forcings to capture the climate impacts of all greenhouse gases other than CO_2.

The SCC represents the marginal cost of climate damages, or the cost of doing nothing about climate change. In a cost-benefit framework, it should be compared to the marginal cost of climate protection. We have compared our SCC estimates to the marginal abatement cost on several versions of a maximum feasible abatement scenario, which would lead to zero or negative net global emissions before the end of this century. In the federal Working Group's analysis, the SCC is well below the abatement cost for these scenarios. We found that under many alternate sets of assumptions, the SCC is roughly equal to or greater than the cost of maximum feasible abatement. This remains true even when the SCC is re-estimated using a rapid-reduction emissions trajectory.

Once the SCC is high enough to justify maximum feasible abatement in cost-benefit terms, then cost-benefit analysis becomes functionally equivalent to a precautionary approach to carbon emissions. All that remains for economic analysis of climate policy is to determine the cost-minimizing strategy for eliminating emissions as quickly as possible. This occurs because the marginal damages from emissions have become so large; the uncertainties explored in our analysis, regarding damages and climate sensitivity, imply that the marginal damage curve could turn nearly vertical at some point, representing a catastrophic or discontinuous change.

The factors driving this result are uncertainties, not known facts. We cannot know in advance how large climate damages, or climate sensitivity, will turn out to be. The argument is analogous to the case for buying insurance: it is the prudent choice, not because we are sure that catastrophe will occur, but because we cannot be sufficiently sure that it will not occur. By the time we know what climate sensitivity and high-temperature damages turn out to be, it will be much too late to do anything about it. The analysis here demonstrates that plausible values for key uncertainties imply catastrophically large values of the SCC.

This result can be generalized to other environmental issues: when there is a credible risk that the marginal damage curve for an externality turns vertical at some threshold (representing discontinuous, extremely large damages), then the shadow price of the externality, such as the SCC, can become so large that cost-benefit analysis turns into cost-effectiveness analysis of the least-cost strategy for staying safely below the threshold.

Our results offer a new way to make sense of the puzzling finding by Martin Weitzman: his "dismal theorem" establishes that under certain assumptions, the

marginal benefit of emission reduction could literally be infinite (Weitzman 2009). The SCC, which measures the marginal benefit of emission reduction, is not an observable price in any actual market. Rather, it is a shadow price, deduced from an analysis of climate dynamics and economic impacts. Its only meaning is as a guide to welfare calculations; we can obtain a more accurate understanding of the welfare consequences of policy choices by incorporating that shadow price for emissions.

Once the shadow price is high enough so that maximum feasible abatement is a welfare improvement, there is no additional meaning to an even higher price. Doubling or tripling the SCC beyond that level would have exactly the same implications for market behavior and policy choices: it would still be optimal to eliminate emissions as rapidly as possible. In this sense, it bears some resemblance to infinity, which is unaffected by doubling or tripling.[19] Our highest SCC estimates are clearly not infinite – but they may be close enough to infinity for all practical purposes.

What's left, finally, of the economic arguments for gradualism in climate policy, which seem to be endorsed by the Working Group's $21/tCO_2$ SCC? To support this approach, given our results, one would have to endorse the Working Group's view of most or all of the key assumptions and uncertainties explored in our analysis: the original DICE damage function, a discount rate of 3 percent, and average rather than 95th percentile climate sensitivity. Changes in these assumptions quickly push the SCC up into the $150-$500 range by midcentury, justifying the maximum feasible pace of abatement; changes in all of these assumptions yield an SCC well above that range. At such levels, cost-benefit analysis provides a result that is identical to a precautionary approach supporting immediate, large-scale action to reduce emissions and avoid dangerous levels of climate change.

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[19] These SCC values bear an even closer resemblance to the concept of "machine infinity" in computer science, i.e. the largest number that a computer can represent. Doubling machine infinity cannot increase it (within that computer), but dividing by two decreases it. The same is true for the practical significance of an SCC estimate which is, for instance, 1.5 times the marginal cost of maximum feasible abatement.

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