ESTIMATING THE SOCIAL COST OF CARBON: AN ALTERNATIVE APPROACH*

by

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PRELIMINARY

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Abstract: An estimate of the social cost of carbon (SCC) is key to the design of climate policy. But how should we estimate the SCC? A common approach is to use an integrated assessment model (IAM), which simulates time paths for the atmospheric CO_2 concentration, its impact on global mean temperature, and the resulting reductions in GDP and consumption. I have argued elsewhere that IAMs have serious deficiencies that make them poorly suited for this job, but what is the alternative? I discuss a simple and more transparent approach to estimating the SCC. It relies on the elicitation of expert opinions regarding (1) the probabilities of alternative economic outcomes of climate change, especially catastrophic outcomes, but not the particular causes of those outcomes; and (2) the reduction in emissions required to avoid or limit those potential outcomes. For example, a possible outcome might be a 20% or greater reduction in GDP. The ratio of the present value of the damages from a catastrophic outcome to the total emission reduction needed to avert the outcome is an estimate of the average SCC.

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1 Introduction.

An estimate of the social cost of carbon (SCC) is a key input to the development of climate policy. The SCC measures the external cost of burning carbon, so pricing carbon at its full social cost (e.g., by imposing a carbon tax) requires an estimate of the SCC.

But how should we estimate the SCC? The most common approach is to use an integrated assessment model (IAM), which simulates time paths for the atmospheric CO_2 concentration (based on assumptions about the path of CO_2 emissions), the impact of a rising atmospheric CO_2 concentration on global mean temperature (and perhaps other measures of climate change), and the reductions in GDP and consumption that will result from rising temperatures. The idea is to start with some base case scenario, i.e., a path for current and future CO_2 emissions (which implies a path for temperature, GDP, etc.). Next, the path for emissions is perturbed by increasing current emissions by one ton, and then calculating a new (and slightly lower) path for consumption. The SCC is then the present value of the reductions in consumption over time resulting from the additional ton of current emissions (based on some discount rate). This is indeed what the Interagency Working Group (IWG) did to estimate the SCC.[1]

I have argued elsewhere that IAMs are poorly suited for this job. One of the most important limitations of IAMs is that some of the equations that go into them — especially the damage functions that translate higher temperatures into reductions in GDP — are ad hoc, with little or no theoretical or empirical grounding.[2] As a result, these models can tell us nothing about the likelihood or possible impact of a catastrophic climate outcome, e.g., a temperature increase above 4°C that has a very large impact on GDP. The reason is that we know very little about the probabilities of very large temperature increases, and we know even less about the likely economic impact of large (or even moderate) temperature increases that occur gradually, over many years. But as I will show in this paper, it is the possibility of a catastrophic climate outcome that is the main driver of the SCC. If we were

[1] The IWG used three IAMs to arrive at estimates of the SCC. See Interagency Working Group on Social Cost of Carbon (2010, 2013). Also, see Greenstone, Kopits and Wolverton (2013) for an illuminating explanation of the process used by the IWG to estimate the SCC.

[2] In Pindyck (2013*a*,*b*, 2015), I explain in detail how and why many of inputs to an IAM are arbitrary, and yet can have a substantial effect on the results the model produces. This is one reason why IAMs differ so widely in their "predictions." Also, IAM-based analyses of climate policy create a perception of knowledge and precision that is illusory, and can thereby mislead policy-makers. For a discussion of some of the advantages and disadvantages of using IAMs to estimate the SCC, see Metcalf and Stock (2015). Burke et al. (2015) note that even coupled general circulation models (GCMs), which typically focus only on climate and do not have a damage function, vary widely in their predictions of changes in temperature and precipitation.

certain that temperature increases and their economic impact will be small or moderate, we would have to conclude that the SCC is small, and climate change is not a major threat to human welfare. Unfortunately we are *not* certain that this "most likely" scenario is what we will indeed experience.

But if we don't use one or more IAMs to estimate the SCC, what can we do instead? This paper provides an alternative approach to estimating the SCC that relies on the elicitation of expert opinions regarding (1) the probabilities of alternative economic outcomes of climate change, and in particular catastrophic outcomes, but *not* the particular causes of those outcomes; and (2) the reduction in emissions that would be required to avoid or limit those potential outcomes. For example, a possible outcome might be a 20% or greater reduction in GDP. Whether that outcome is the result of a large increase in temperature but moderate impact of temperature on GDP, or the opposite, is not of concern. (Experts could easily disagree about this.) What matters is simply the likelihood of such an outcome, and the amount of abatement needed to avert that outcome. Compared to the use of one or more IAMs, the result is a more straightforward and transparent approach to estimating the SCC.

Focusing on catastrophic outcomes both simplifies and complicates the problem of estimating the SCC. It simplifies the problem by allowing us to focus on only a subset of possible economic outcomes, namely the more extreme ones, and not on the causes of the outcomes. This is consistent with the very notion of an SCC — the economic harm caused by emitting an additional ton of CO_2, irrespective of the economic and climate mechanisms that generate the harm. What we have to worry about is the possibility of a climate-induced drop in GDP so large as to be considered catastrophic. (Of course climate change could also cause non-economic damages, such as greater morbidity and mortality, the extinction of species, and social disruptions. I am assuming, as is typically done in the estimation of the SCC, that these non-economic damages could all be monetized and included as part of the drop in GDP.)

Focusing on catastrophic outcomes also complicates matters, because we know so little about the likelihood that they will occur. But that in turn supports the approach I take here. The use of a complex IAM or related model throws a curtain over our lack of knowledge, and creates a veneer of scientific legitimacy that suggests we know more than we do. The use of expert elicitation, on the other hand, is simple and transparent, and summarizes the views (however obtained) of researchers who have studied climate change and its impact.

How do we know that the possibility of a catastrophic outcome is what matters for the SCC? Because unless we are ready to accept a discount rate on consumption that is extremely small (e.g., around 1%), the "most likely" scenarios for climate change simply cannot generate enough damages – in present value terms – to matter.[3] That is why the Interagency Working Group, which used a 3% discount rate, obtained the rather low estimate of $33 per ton for the SCC (recently updated to $39). Using some simple examples, I will show that low-probability but severe outcomes can dominate an estimate of the SCC.

One might argue that the approach suggested here involves a model of sorts, but it is a model that has very few moving parts, and is thus much more transparent than an IAM-based analysis. It works as follows:

1. The primary object of analysis is the economic impact of (anthropomorphic) climate change, where economic impact is measured by the reduction in GDP (broadly defined so as to include indirect non-economic impacts such as greater morbitity and mortality). One could argue, based on both theory and empirical evidence, that climate change will affect the *growth rate* of GDP rather than its level, but to estimate an SCC we would have to compute how changes in the growth rate affect the level of GDP and consumption over time.[4] I skip that step and work directly with levels (as is done in all of the IAM-based analyses that I am aware of).

2. I ignore the mechanisms by which ongoing CO_2 emissions can cause climate change, and by which climate change can reduce GDP, mechanisms that many would argue are quite complex and poorly understood. I care only about the *outcomes* that can result from CO_2 emissions. Also, I focus largely on catastrophic outcomes, i.e., climate-caused percentage reductions in GDP that are large in magnitude.

3. I want to know the probabilities of these outcomes. For example, what is the probability that under "business as usual" (BAU), i.e., no significant global emissions abatement beyond that mandated by current policy, we will experience a climate-induced reduction in GDP 50 years from now of at least 10 percent? (In other words, what is the probability that GDP 50 years from now will be 10 percent lower than it would be with no climate change?) What is the probability of climate-induced 20-percent or greater reduction in GDP? A 50-percent reduction? I will rely on expert opinion to get answers to these questions.

[3]I have shown this in Pindyck (2011*b*, 2012), and will further demonstrate it in the next section.

[4]For the theoretical arguments, see Pindyck (2011*b*, 2012) and the references therein. For empirical evidence, see Dell, Jones and Olken (2012) and Bansal and Ochoa (2011). Most economic studies of catastrophes and their impact are likewise based on level effects; see, e.g., Barro (2013), Martin (2008) and Martin and Pindyck (2015).

4. Next, I want to know the emission reductions that would be needed to avert one or more of these outcomes. Start with an expected growth rate of CO_2 emissions under BAU. By how much would that growth rate have to be reduced to avoid a climate-induced reduction in GDP 50 years from now of 20 percent or more? Once again, I will rely on expert opinion for answers.

5. With this information on outcome probabilities and emission reductions, I will compute an *average* SCC, as opposed to the more conventional *marginal* SCC obtained from simulating IAMs. An average SCC has the advantage of providing long-run policy guidance, as explained later.

For an economist, relying on expert opinion might not seem very satisfying. Economists often build models to avoid relying on subjective (expert or otherwise) opinions. But remember that the inputs to IAMs (equations and parameter values) are already the result of expert opinion; in this case the modeler is the "expert." This is especially true when it comes to climate change impacts, where theory and data provide little guidance. Also, we would expect that that different experts will arrive at their opinions in different ways. Some might base their opinions on one or more IAMs, others on their studies of climate change and its impact. The methods experts use to arrive at their opinions is not a variable of interest; what matters is that the experts are selected based on their established expertise.[5]

Experts, of course, are likely to disagree, particularly when it comes to climate change, where our knowledge is so limited. But focusing on catastrophic outcomes, and the emission reductions needed to eliminate those outcomes, may reduce the extent of disagreement, and will at least center the debate on what really matters as the driver of policy. Compared to agreeing on the details of some IAM, it should be less difficult for climate scientists and economists to reach a consensus on the answers to the questions raised above, or agree on a range of answers.

In the next section I begin with a simple (hypothetical) example of a set of possible climate outcomes and their probabilities, of the sort that might be elicited from climate experts. I also show how a set of expert opinions regarding outcomes and probabilities can be translated into one or more outcome probability distributions. I then explain my approach to calculating the SCC, which I illustrate using the same example of possible

[5]As discussed later, experts will be selected based on their publications in relevant refereed journals. I am certainly not the first to utilize expert opinion as an input to climate policy; see, e.g., Nordhaus (1994), Kriegler et al. (2009), Zickfeld et al. (2010) and Morgan (2014). For related expert elicitations of the long-run discount rate, see Drupp et al. (2015) and Weitzman (2001).

Table 1: PROBABILITIES OF CLIMATE IMPACTS FROM A HYPOTHETICAL EXPERT.

HORIZON $T = 50$

% GDP Reduction, z	0	0.020	0.050	0.100	0.200	0.500
$\phi = -\ln(1-z)$	0	0.020	0.051	0.105	0.223	0.693
Prob	.25	.50	.10	.06	.05	.04
$1 - F(\phi)$	1	.75	.25	.15	.09	.04

HORIZON $T = 150$

% GDP Reduction, z	0	0.020	0.050	0.100	0.200	0.500
$\phi = -\ln(1-z)$	0	0.020	0.051	0.105	0.223	0.693
Prob	0	.22	.40	.20	.10	.08
$1 - F(\phi)$	1	1	.78	.38	.18	.08

outcomes, along with some assumptions about the emission reductions needed to avoid some of these outcomes. In particular, I focus on the emission reductions needed to truncate the outcome distribution, i.e., cut the tail of the distribution at some point. I then discuss the selection of experts, and present the questionnaire that will be used to elicit the opinions I need. Finally, as an example of the kinds of results we might get, I show the responses to the questionnaire from 11 experts (who attended a recent climate change conference), and I calculate the SCC implied by these responses.

2 Climate Impact Outcomes.

Here is a question to be asked of experts: Under "business as usual" (BAU), i.e., little or no GHG abatement beyond current policies and projections, what is the probability that T years from now (perhaps $T = 50$) climate change will result in a percentage drop in GDP, z, of at least 2%? What about a drop in GDP of at least 5%? 10%? And then at the catastrophic end, 20% and 50%. The answers might look something like those in the top part of Table 1, where F is the cumulative distribution corresponding to the probabilities in the third row.

Next, define $\phi = -\ln(1-z)$. Let Y_0 denote what GDP will be if there is no climate change (or if there is climate change but it has no impact). Then a climate change outcome z implies that GDP will be $e^{-\phi}Y_0$. Why introduce ϕ? Because I want to fit several probability distributions for ϕ to "expert opinion" damage numbers of the sort shown in Table 1. While z is constrained to $0 \leq z \leq 1$, ϕ is unconstrained at the upper end. (For example, $\phi = 4.6$ corresponds to $z = .99$.) Thus I can compare the fits of both fat-tailed (e.g., Generalized

Pareto) and thin-tailed (e.g., Gamma) distributions to "expert opinion" damage numbers, and also compare the implications of these different distributions for SCC estimates. This is useful because some have argued that the distribution is indeed fat-tailed, and a fat-tailed distribution can imply a high SCC.[6] Also, given some distribution, I can change the mean, variance, or other moments and determine its impact on the SCC. I denote the distribution for ϕ by $f(\phi)$. For example, a natural distribution for ϕ is the Generalized Pareto distribution, which is fat-tailed:

$$f(\phi) = k\alpha(\phi - \theta)^{-\alpha-1} \ , \quad \phi \geq \theta + k^{1/\alpha} \tag{1}$$

The value of α determines the "fatness" of the tail; the smaller is α the fatter is the tail. If $\alpha > n$, the first n moments exist. Fitting the cumulative distribution to the numbers in the top half of Table 1 yields $\alpha = 0.774, \theta = -0.00976$, and $k = 0.0305$. (In this case, $\alpha < 1$, so none of the moments exist, and we can say that the fitted distribution is extremely fat.)

2.1 Impact Over Time.

The top panel of Table 1 shows probabilities of various climate-induced reductions in GDP only at a specific horizon $T = 50$ years. However, we would expect the impact of climate change to begin before T and continue and increase in magnitude after T. In other words, we want to allow for a percentage reduction in GDP that increases over time, but eventually levels out at some maximum value.

To make the dynamics as simple as possible, I will assume that under BAU, $\phi_t = -\ln(1-z_t)$, and thus the percentage reduction in GDP, z_t, varies over time as follows:

$$\phi_t = \phi_m[1 - e^{-\beta t}] \tag{2}$$

Thus ϕ_t starts at 0 and approaches a maximum value of ϕ_m at a rate given by β. We want to calibrate the maximum reduction ϕ_m and the parameter β.

Suppose we have average numbers for z_t and thus ϕ_t at two different points in time, T_1 and T_2. We denote those averages for ϕ_t by $\bar{\phi}_1$ and $\bar{\phi}_2$. These numbers would be based on expert opinion. The bottom panel of Table 1 shows probabilities of alternative impacts at a longer horizon, $T_2 = 150$ years (from the same hypothetical "expert"). Using the numbers in Table 1, with $T_1 = 50$ and $T_2 = 150$, $\bar{z}_1 = \mathbb{E}(z_1) = .05$ so that $\bar{\phi}_1 = .051$, and $\bar{z}_2 = \mathbb{E}(z_2) = .10$ so that $\bar{\phi}_2 = .105$. Then we can use eqn. (2) to determine β:

$$[1 - e^{-\beta T_2}]/[1 - e^{-\beta T_1}] = \bar{\phi}_2/\bar{\phi}_1 \tag{3}$$

[6]See Weitzman (2009, 2011). For an opposing point of view, see Pindyck (2011*a*).

For the numbers in Table 1, $\bar{\phi}_2/\bar{\phi}_1 = 2.06$, so the solution to eqn. (3) is roughly $\beta = .01$. I take this parameter as fixed (non-stochastic).

This leaves the maximum impact ϕ_m, which I treat as stochastic. Given a value for β, the distribution for ϕ_m follows directly from a distribution for ϕ_1, which in turn would be derived from a range of expert opinions (e.g., for $T_1 = 50$). As a simple example, a distribution for ϕ_1 could be derived from the top part of Table 1. Given that distribution, from eqn. (2):

$$\tilde{\phi}_m = \tilde{\phi}_1/[1 - e^{-\beta T_1}] \tag{4}$$

It is important to note that eqn. (3) will not have a positive solution for β if $\bar{\phi}_2/\bar{\phi}_1$ is too large. With $T_1 = 50$ and $T_2 = 150$, $\bar{\phi}_2/\bar{\phi}_1 = 2.06$ implies that β is about .01, but if $\bar{\phi}_2/\bar{\phi}_1$ were 3 or greater, the solution to eqn. (3) would be negative. It is quite possible that expert opinion will yield a ratio $\bar{\phi}_2/\bar{\phi}_1$ that is "too large," in the sense that the resulting value of β is negative. Should that be the case, I will constrain β to be .005, which implies that $\tilde{\phi}_m$ is roughly four times as large as $\tilde{\phi}_1$.

2.2 GDP Over Time.

I will assume that absent any impact of climate change, GDP and consumption would grow at the constant rate g. Benefits of abatement are measured in terms of avoided reductions in GDP, not just consumption, so I include avoided reductions in investment and government spending as part of the benefits of abatement. GDP begins at its (actual) initial value Y_0, and its value at any future time t is $(1 - z_t)Y_0e^{gt} = Y_0e^{gt-\phi_t}$.

What is the loss from climate-induced reductions in GDP? At any point in time, that loss is just $z_tY_0e^{gt} = (1 - e^{-\phi_t})Y_0e^{gt}$. Thus the distribution for z_1 (which follows from the distribution for ϕ_1) yields the distribution for climate damages in each period. As discussed below, that distribution is the basis for the benefit portion of our SCC calculation.

3 Estimating the SCC.

We can calculate a social cost of carbon (SCC) consistent with expert opinions of the sort illustrated by the numbers in Table 1 if we also have data (or expert opinions) as to the percentage reduction in GHG emissions that would be required to avoid some range of outcomes. For example, using the numbers in Table 1, we could ask how much emissions would have to be reduced to avoid the very worst or two worst scenarios in the top part of the table. In this case we would measure benefits as the present value of the expected avoided reduction in the flow of GDP. This, of course, requires that we posit a discount rate, which I denote by R.

This estimate of the SCC begins with a scenario for the objective of GHG abatement. That scenario would likely be the truncation of the tail of the impact distribution (such as, in the context of the top panel of Table 1, eliminating outcomes of $z \geq .20$). Let B_0 denote the present value of the resulting expected avoided reduction in the flow of GDP. Next, we need the "cost" of this abatement scenario, not in dollar terms, but in terms of the total amount of required emission reductions over some horizon. Let ΔE denote this total amount of reduced emissions, measured in tons of CO_2. Given B_0 and ΔE, the SCC is simply calculated as $B_0/\Delta E$. As discussed in more detail below, this an *average*, not a marginal, measure of the SCC.[7]

Why focus on eliminating the tail of the impact distribution? First, eliminating *any* future impact of climate change is most likely impossible, and thus not an interesting or informative scenario. Second and more importantly, the tail of the distribution accounts for most of the expected damages from climate change under BAU (as I will illustrate shortly with some examples). Thus avoiding possible catastrophic damages, as opposed to avoiding *any* damages, should be the primary objective of climate policy.

3.1 Benefits from Abatement.

The SCC calculation begins with a probability distribution for the impact of climate change under BAU. Next, we introduce a scenario for the truncation of that impact distribution, e.g., the elimination of outcomes of $z \geq .20$, which corresponds to $\phi \geq .223$. We can then use eqns. (2) and (3) to calculate the benefit from truncating the distribution. For simplicity, I express damages below in terms of z rather than $\phi = -\ln(1-z)$.

Note that the benefit from eliminating *any* climate impact (an unlikely scenario) is

$$\begin{aligned} B_0 &= \mathbb{E}_0(z_m) Y_0 \int_0^\infty [1 - e^{-\beta t}] e^{(g-R)t} dt \\ &= \frac{\beta Y_0}{(R-g)(R+\beta-g)} \mathbb{E}_0(z_m) \\ &= \frac{\beta Y_0}{(R-g)(R+\beta-g)(1-e^{-\beta T_1})} \mathbb{E}_0(z_1) \end{aligned} \tag{5}$$

[7]Note that this is a different way of computing the SCC than what is usually done using IAMs, and what was done by the Interagency Working Group. The typical approach is to begin with a path of emissions and then increase only *this year's* emissions by one ton. The resulting flow of marginal damages ("resulting" according to the IAM) is discounted back to today to compute the SCC. See, e.g., Interagency Working Group on Social Cost of Carbon (2010, 2013) and Greenstone, Kopits and Wolverton (2013).

Here, $\mathbb{E}_0(z_1)$ denotes the expectation of z_1 based on the full distribution of possible outcomes. It is more realistic and informative, however, to instead calculate the benefit from truncating the distribution, i.e., eliminating part of the right-hand tail. Let $\mathbb{E}_1$ denote the expectation of z_1 over the truncated distribution of impacts. Then the benefit from truncating the distribution is

$$B_0 = \frac{\beta Y_0[\mathbb{E}_0(z_1) - \mathbb{E}_1(z_1)]}{(R-g)(R+\beta-g)(1-e^{-\beta T_1})} \,. \tag{6}$$

In eqn. (6), $\beta Y_0[\mathbb{E}_0(z_1) - \mathbb{E}_1(z_1)]/(1-e^{-\beta T_1})$ is the instantaneous flow of benefits from truncating the outcome distribution, and dividing by $(R-g)(R+\beta-g)$ yields the present value of this flow. For example, in the top panel of Table 1, $\mathbb{E}_0(z_1) = .05$. Suppose by reducing emissions we can eliminate outcomes of $z \geq .20$. Increasing the other probabilities so they sum to one, we would then have $\mathbb{E}_1(z_1) = .022$. Setting $\beta = .01$, $g = .02$ and $R = .04$, this implies $B_0 = .00071Y_0/.0006 = 1.19Y_0$. Note that in the *first year*, the benefit from this abatement policy would be less than 0.1% of GDP, but the annual benefit rises over time (as z_t rises), so B_0, the present value of the flow of annual benefits, is greater than current GDP.

3.2 Required Emission Reductions.

To get an estimate of the SCC, we also need to know how much emissions would have to be reduced in order to eliminate part or all of the possible climate-induced reductions in GDP. Consider the example of eliminating the two worst outcomes in Table 1, i.e., $z \geq .20$. Suppose emissions this year are at a level E_0, and under BAU are expected to grow at the constant rate m_0. Suppose further that the expert consensus is that to eliminate these worst outcomes, the growth rate of emissions would have to be reduced to $m_1 < m_0$. (Note that m_1 could, and probably would be negative.) We want the sum of all future emission reductions, ΔE, which we will compare to B_0.

If the cost of reducing emissions were very small, any positive SCC would justify a large reduction in emissions. But the cost of reducing emissions, at least by a large amount, is not small. One advantage of calculating a *marginal* SCC (as is usually done, e.g., with an IAM) is that we do not need to estimate the cost of reducing emissions, or the amount by which emissions should be reduced. We would expect that if a carbon tax equal to the SCC is imposed, along the optimal trajectory today's emissions will be reduced up to the point that the marginal cost of the last ton abated will equal the SCC. Of course this marginal SCC will vary over time, so that the size of the carbon tax would likewise have to vary.

How should we calculate the sum of current and future emission reductions, ΔE? One possibility is to simply add up the total reduction in emissions from $t = 0$ to some horizon T. One problem with this approach is that the horizon T is arbitrary. A second problem is that assuming abatement costs are constant, in present value terms it is cheaper to abate more in the future than today. Because I calculate an *average* SCC over an extended period of time, I need to consider that future costs of abatement (like future benefits) must be discounted.

Rather than simply adding up total required emission reductions, I will assume that the real cost per ton abated is constant over time.[8] Then, irrespective of the particular value of that cost, I can discount future required emission reductions at the same rate R used to discount future benefits (as long as $m_0 < R$). In that case we can ignore the horizon T and simply calculate ΔE as the present value of the flow of emissions at the BAU growth rate m_0 less the present value at the reduced growth rate m_1:

$$\begin{aligned}\Delta E &= E_0 \int_0^\infty \left[e^{(m_0-R)t} - e^{(m_1-R)t}\right] dt \\ &= \frac{(m_0 - m_1)E_0}{(R-m_0)(R-m_1)} \end{aligned} \tag{7}$$

In eqn. (7), the term $(m_0 - m_1)E_0$ is the instantaneous (current) reduction in emissions, and dividing by $(R-m_0)(R-m_1)$ yields the present value of the flow of emission reductions. For example, if the abatement policy is to reduce the growth rate of emissions from $m_0 = .02$ to $m_1 = -.02$, and if $R = .04$, $\Delta E = .04E_0/.0012 = 33.3E_0$, i.e., this year's abatement is 4% of current annual emissions, but the present value of all current and future emission reductions is about 30 times this year's emissions.

3.3 Average Social Cost of Carbon.

The average social cost of carbon is just the ratio of B_0 to ΔE. Using eqns. (6) and (7), we can write this as:

$$S = \frac{\beta Y_0[\mathbb{E}_0(z_1) - \mathbb{E}_1(z_1)]/(1-e^{-\beta T_1})}{(m_0 - m_1)E_0} \times \frac{(R-m_0)(R-m_1)}{(R-g)(R+\beta-g)} \tag{8}$$

The first fraction on the RHS of eqn. (8) can be thought of as an instantaneous SCC, i.e., the current benefit (in dollars) divided by the current reduction in emissions (in metric tons). This instantaneous SCC is a flow variable, and the second fraction puts this flow in present

[8] The real cost per ton abated will be affected over time by two factors that work in opposite directions. Technological progress, e.g., the development of cheaper and better alternatives to fossil fuels, will reduce the cost over time. On the other hand, abatement becomes more and more difficult (and costly) as emissions are continually reduced. It unclear which of these effects will dominate, so it is reasonable for purposes of estimating the SCC to assume that the cost is constant.

value terms. Thus S is the present value of the flows of benefits and emission reductions that extend throughout the indefinite future.

It is important to be clear about how this average SCC differs from the marginal SCC. The marginal SCC is the present value of the flow of benefits (in terms of avoided GDP reductions) from a one-ton reduction in today's emissions. The flow of benefits is (typically) found by simulating an IAM with and without a one-ton change in today's emissions. The average SCC of eqn. (8), on the other hand, is the present value of the flow of benefits from a much larger reduction in emissions now and throughout the future, divided by the total size of the reduction. The marginal calculation is consistent with the way environmental economists usually measure the social cost of a pollutant, so why work with an average number?

First, as a guide for policy, the marginal SCC is of limited use. It can tell us what *today's* carbon tax should be, assuming that total emissions, now and in the future, are on an optimal trajectory, which is a strong assumption. Second, the marginal SCC will change over time, which implies a carbon tax that (along the optimal trajectory) likewise changes over time. It is hard to imagine a climate policy that is based on a carbon tax that changes year by year.[9] The average SCC provides a guideline for policy over an extended period of time, which can be more useful, especially given the difficult and protracted process for actually agreeing on a climate policy.

In addition, this average SCC is much less sensitive to the choice of discount rate R than is the marginal SCC. The marginal SCC is the present value of the flow of benefits from a one-ton change in current emissions; an increase in R reduces that present value, but does nothing to the one-ton change in emissions. The average SCC of eqn. (8), on the other hand, is the present value of a flow of benefits relative to the present value of a flow of emission reductions. Thus there is an offsetting effect of a higher discount rate, via the numerator of the second fraction in eqn. (8). The numerical examples shown below illustrate this reduced sensitivity to the discount rate.

Finally, the marginal calculation requires the use of an IAM or related model with its many assumptions regarding the damage function, etc., and often its lack of transparency. Calculating a marginal SCC does not lend itself to expert elicitation, because experts cannot tell us what will happen if we reduce emissions today (and only today) by one ton. And even if we had confidence in the particular IAM that is used, the calculated SCC will be

[9] Generally the marginal SCC will rise over time, even if the damage function is linear over some range, for the same reason that the competitive (and socially optimal) price of a depletable resource will rise over time. Think of the unpolluted atmosphere as a resource that gets depleted as GHG emissions accumulate.

sensitive to the assumption made regarding the base-case time path for CO_2 emissions used in the simulations.

3.4 Numerical Examples.

Here are some simple numerical examples based on the impact and probability numbers in Table 1, and using data for world GDP and world GHG emissions. World GHG emissions (CO_2e) in 2013 were about 33 billion metric tons. The average growth rate of world GHG emissions from 1990 through 2013 was approximately 3%. The U.S. and Europe had roughly zero emission growth over that period; almost all of the 3% growth was due to increased emissions from Asia, and those emission are likely to slow over the coming decades, even without some kind of international climate agreement. Thus I will assume that under BAU emissions would grow over the indefinite future at an annual rate of 2% (so $m_0 = .02$). Also, world GDP in 2013 was about $Y_0 = \$75$ trillion. I will take the real (per capita) growth rate of GDP to be $g = .02$, and use a discount rate of $R = .04$. I will base outcome probabilities on Table 1. The numbers in Table 1 imply that the parameter β in eqn. (2) is about 0.01.

Suppose that by reducing the growth rate of emissions from $m_0 = .02$ to $m_1 = -.02$ we could avoid the two "catastrophic" outcomes in Table 1, i.e., $z = .20$ and $z = .50$. In the top part of Table 1, $\mathbb{E}_0(z_1) = .05$, and $\mathbb{E}_1(z_1) = .022$. (The latter is the expected value of z_1 for the truncated distribution, i.e., with the two worst outcomes eliminated.) From eqn. (6), the benefit of avoiding these outcomes is $B_0 = 42.36 \times Y_0(.05 - .022) = 1.186 \times Y_0 = \$89 \times 10^{12}$. Given 2013 emissions, the assumed 2% growth rate of emissions under BAU, a discount rate $R = .04$, and the assumption that $m_1 = -.02$, from eqn. (7), $\Delta E = 1.10 \times 10^{12}$ metric tons. Using these numbers, we get an implied SCC = $B_0/\Delta E = \$81$ per metric ton.

Recall from eqn. (8) that we can express the SCC as the product of two fractions. The first is the ratio of the current (annual) benefit flow to the current (annual) reduction in emissions. The second fraction puts these flows in present value terms, accounting for the growth of benefits and the growth of abatement. In this numerical example, the first fraction, i.e, the current instantaneous SCC, is $.00071Y_0/.04E_0 = 5.33 \times 10^{10}/1.32 \times 10^9 = \$40.4$ per metric ton. The second fraction is $.0012/.0006 = 2$, yielding the present value SCC of about \$81 per metric ton.

How does this result depend on the discount rate R? Table 2 shows the SCC and its components for discount rates ranging from .025 to .060. (Recall that we must have $R > g$ and $R > m_0$, which means $R > .02$.) As one would expect, the benefit from truncating the outcome distribution, B_0, declines sharply as R is increased; this is the reason that estimates

Table 2: Sensitivity of SCC to Discount Rate.

R	B_0	ΔE	SCC
.025	712×10^{12}	5.87×10^{12}	\$121
.030	267×10^{12}	2.64×10^{12}	\$101
.040	89×10^{12}	1.10×10^{12}	\$81
.060	26.7×10^{12}	0.41×10^{12}	\$65

Note: B_0 is the benefit from truncating the distribution for z in Table 1, eliminating outcomes of $z \geq .20$, and is given by eqn. (6). ΔE is the required total reduction in emissions, given by eqn. (7), with the emission growth rate reduced from $m_0 = .02$ to $m_1 = -.02$. SCC $= B_0/\Delta E$. Also, $\beta = .01$, $g = .02$, and $T_1 = 50$ years.

of the marginal SCC obtained from IAMs are so sensitive to the discount rate. But note that total emission reduction, ΔE, also declines as R is increased, because the value of future emissions is discounted. The net result is that the (average) SCC declines as R is increased, but far less sharply.

As another example, consider the elimination of *any* climate change impact. This goal is probably impossible (global mean temperature would continue to rise even if emissions were immediately reduced to zero), but as an illustrative example, we will assume that reducing the growth rate to $m_1 = -.05$ would do the job. To get the corresponding SCC, note that from eqn. (5), $B_0 = 2.12Y_0 = \$159 \times 10^{12}$. We calculate ΔE using eqn. (7), and get $\Delta E = 1.28 \times 10^{12}$, which implies an SCC of $B_0/\Delta E = \$124$ per metric ton.

3.5 Importance of Catastrophic Outcomes.

I claimed earlier that much of the SCC is attributable to the possibility of a catastrophic outcome. This is easy to see from the calculations of B_0 in the simple examples shown above. From eqn. (5), the benefit from avoiding *any* climate change impact is

$$B_0 = \frac{\beta Y_0}{(R-g)(R+\beta-g)(1-e^{-\beta T_1})}\,\mathbb{E}_0(z_1)\,.$$

According to our hypothetical expert, the benefit from avoiding only the two "catastrophic" outcomes, i.e., avoiding $z \geq .20$, is the same, but with $\mathbb{E}_0(z_1)$ replaced by $[\mathbb{E}_0(z_1) - \mathbb{E}_1(z_1)]$. Thus the fraction of the total benefit from eliminating any impact attributable to the catastrophic outcomes is $1 - \mathbb{E}_1(z_1)/\,\mathbb{E}_0(z_1)$. For the numbers in the top part of Table 1, this fraction is roughly 60%.

The most extreme outcome in the top part of Table 1, $z = .50$, has an estimated probability of only .04 of occurring (and the probability of $z = .2$ or $z = .5$ is .09). But an outcome of this magnitude amounts to a far greater total loss of GDP than the expected value $\mathbb{E}_0(z_1) = .05$.

Of course the SCC that I measure also depends on the reduction in emissions required to eliminate some or all climate impacts. We would expect the elimination of *any* climate outcome to require a far greater reduction in the growth rate of emissions than would the elimination of only an extreme outcome. In the numerical example above, I assumed a reduction in the growth rate to $m_1 = -.02$ would be sufficient to eliminate a catastrophic outcome, and (probably unrealistically) a reduction to $m_1 = -.05$ would eliminate any outcome. Using this latter case as a benchmark, I calculated an SCC of \$124 per metric ton. But now suppose the probability of $z_1 = .2$ or $z_1 = .5$ is zero. Scaling up the other probabilities in the top part of Table 1 so they sum to 1, the expected impact is now $\mathbb{E}_0(z_1) = .022$. Suppose once again that we can avoid *any* impact by reducing the growth rate to $m_1 = -.05$, so that $\Delta E = 1.28 \times 10^{12}$. But now $B_0 = 69 \times 10^{12}$, which implies an SCC of $B_0/\Delta E = \$55$. Compare this to the SCC of \$124 when there was a .09 probability of $z_1 \geq .20$; eliminating the possibility of these catastrophic outcomes reduces the SCC by more than half.

4 Distribution for Outcomes.

The numbers in Table 1 only provide six discrete values for z (and ϕ) and six corresponding probabilities, corresponding to a single hypothetical expert. But we can fit these numbers to one or more continuous probability distributions. Doing so will provide information on what distribution best fits these similar numbers, and what the implied "far tail" of the distribution looks like, i.e., what are the implied probabilities of outcomes even worse than a 50% drop in GDP. Most important, we can fit distributions to a whole set of expert opinions regarding outcomes and probabilities, and thereby calculate an SCC from those numbers. I will examine three distributions for ϕ: a generalized Pareto distribution, a lognormal distribution, and the (thin-tailed) Gamma distribution. The generalized Pareto distribution is perhaps the most logical candidate for this exercise, in part because it is simple and it allows for a fat tail.

The generalized Pareto distribution is given by:

$$f(\phi) = k\alpha(\phi - \theta)^{-\alpha-1}\ , \quad \phi \geq \theta + k^{1/\alpha} \tag{9}$$

The cumulative distribution function is:

$$F(\phi) = 1 - k(\phi - \theta)^{-\alpha} \tag{10}$$

The value of α determines the "fatness" of the tail; if $\alpha > n$, the first n moments exist.[10]

The fat tail means that $f(\phi)$ declines toward zero more slowly than exponentially, so that expectations of ϕ or functions of ϕ can (depending on the value of α) blow up. Thus we approximate such expectations by integrating to some maximum (but finite) value of ϕ, which I denote by $\phi_{\max}$. Typically we set $\phi_{\max} = 4.6$, which corresponds to $z_{\max} = .99$. Thus $\mathbb{E}_0(z_1) = 1 - \mathbb{E}_0(e^{-\phi})$ in eqns. (5) and (6) is calculated as

$$\mathbb{E}_0(z_1) = 1 - \int_{\theta+k^{1/\alpha}}^{\phi_{\max}} k\alpha(\phi-\theta)^{-\alpha-1}e^{-\phi}d\phi \tag{11}$$

Suppose $\mathbb{E}_1(z_1) = 1 - \mathbb{E}_1(e^{-\phi})$ is the expectation of z_1 when the distribution has been truncated to eliminate outcomes for ϕ that are greater than $\phi_1 > \theta + k^{1/\alpha}$. Then $\mathbb{E}_1(z_1)$ is calculated as

$$\mathbb{E}_1(z_1) = 1 - \frac{1}{F(\phi_1)}\int_{\theta+k^{1/\alpha}}^{\phi_1} k\alpha(\phi-\theta)^{-\alpha-1}e^{-\phi}d\phi \tag{12}$$

I will also fit a lognormal distribution and gamma distribution to the set of outcome probabilities elicited from experts. The lognormal distribution is given by:

$$f(\phi) = \frac{1}{\sqrt{2\pi}\sigma\phi}\exp\left[\frac{-(\ln\phi-\mu)^2}{2\sigma^2}\right]\ , \quad \phi \geq 0 \tag{13}$$

and the gamma distribution is given by:

$$f(\phi) = \frac{\lambda^r}{\Gamma(r)}\phi^{r-1}e^{-\lambda\phi}\ , \quad \phi \geq 0 \tag{14}$$

where $\Gamma(r)$ is the gamma function. Note that for all $r \geq 0$ and $\lambda \geq 0$, the gamma distribution is thin-tailed. The lognormal distribution approaches zero exponentially, and is thus intermediate between a fat- and thin-tailed distribution.

I will estimate the parameters of each distribution from a least-squares fit of each corresponding cumulative distribution to the set of expert opinions regarding outcomes and probabilities. Which of the three distributions is "best?" Barring some theoretical argument for ranking these distributions, I can simply compare how they fit the "data" using the corrected R^2. At the end of the next section, I show how this is done using the preliminary survey responses of 11 experts.

[10]The first four moments of this distribution (when they exist) are: Mean $= \theta + \frac{\alpha}{\alpha-1}k^{1/\alpha}$, Variance $= \frac{\alpha k^{2/\alpha}}{(\alpha-1)^2(\alpha-2)}$, Skewness $= 2\frac{(\alpha+1)}{(\alpha-3)}\left(\frac{\alpha-2}{\alpha}\right)^{1/2}$, and Ex. Kurtosis $= \frac{3(\alpha-2)(3\alpha^2+\alpha+2)}{\alpha(\alpha-2)(\alpha-4)} - 3$.

5 Choice of Experts, Questionnaire, and Some Initial Results.

I will survey economists and climate scientists to elicit their opinions regarding possible outcomes and the emission reductions needed to avoid some of those outcomes. Those opinions will include probabilities along the lines of those in Table 1, to which I will fit the distributions shown above. In addition, I want an estimate of the average (or most likely) outcome at a more distant point in the future, so that I can estimate the parameter β in eqn. (3). In this section I explain how experts will be identified, I present the questionnaire they will be given, and to provide a rough idea of what the results might look like, I show the responses of 11 experts (who attended a recent conference), along with the implications of those responses for the SCC.

5.1 Identification of Experts.

I am interested in the opinions of people with significant research experience and expertise in climate change and its impact. This can include climate scientists, economists who have worked on climate change impacts and climate policy, as well as individuals whose main focus has been on policy design. What matters is that they have established expertise.

To identify experts for inclusion in the study, and to be as broad and inclusive as possible, Web of Science was used to identify journal articles, book chapters, reviews, and other scholarly publications on climate change and its impacts that were published during the last 10 years. The Web of Science advanced search capabilities were used to search publication titles, abstracts, and assigned keywords for particular climate change-related search terms. This initial search was conducted in November 2015 and returned approximately 50,000 publications. A list of all search terms used, including Boolean operators where relevant, is provided in Table 3 below; all results included at least one search term from column A, or at least one search term from *each of* columns B and C.

This search will yield publications written by environmental and climate scientists as well as economists who have studied climate change and climate change policy. (These groups can be separated, as discussed later.) However, an initial search yields publications that were also written by medical researchers, architects and planners, and others, and on review, these publications had little or nothing to do with climate change and its impact. Thus, to isolate environmental and climate scientists and economists, we subsequently filtered results to include only publications in research areas as defined by Web of Science, based on the content of the publications: agriculture, business and economics, environmental sciences and

Table 3: Web of Science Climate Change Search Terms.

Single Search Terms	Joint Search Terms	
(A)	(B)	(C)
“climate change policy”	“ocean temperature”	“climate change”
“social cost of carbon”	“precipitation	“climate-change”
“climate policy”	“sea level rise”	“greenhouse gas”
“climate-change policy”	“sea level change”	“greenhouse gases”
“climate forcing”	“ocean acidity”	GHG
“radiative forcing”	catastrophe	(CO2 AND emissions)
“climate feedbacks”	catastrophic	(“carbon dioxide” AND emissions)
“ climate sensitivity”	economy	
“equilibrium climate response”	economics	
“global mean surface temperature”	damages	
“carbon price”	mortality	
“carbon-price”	productivity	
“price of carbon”	risk	
“carbon tax”	“discount rate”	
“tax on carbon”	“atmospheric concentration”	
(“cap-and-trade” AND carbon)	GDP	
(carbon AND quota)	“gross domestic product”	
(carbon AND trade AND cap)		

Note: Quotation marks indicate that phrase must appear exactly as written. Search results must include at least one search term in column A *or* at least one search term from *each of* columns B and C.

Table 4: PUBLICATIONS AND AUTHORS BY WEB OF SCIENCE RESEARCH AREA.

Research Area	(A) No. Pubs, Top 10% of Cites	(B) Distinct Authors	(C) No. Authors per Pub.	(D) No. Authors, 2.50 per Pub.	(E) % of Highly Cited Pubs.	(F) % of Authors
Agriculture	282	1506	5.34	705.6	7.3%	7.3%
Business and Economics	257	643	2.50	643.0	6.7%	6.7%
Environmental Sciences and Ecology	1873	8932	4.77	4686.1	48.6%	48.6%
Geology	629	3787	6.02	1573.7	16.3%	16.3%
Meteorology and Atmospheric Sciences	815	4919	6.04	2039.1	21.1%	21.1%
Total	3856	19,787	4.93	9647.5	100%	100%

Note: Adjustment in last three columns matches percentage of authors to percentage of highly cited publications in each area.

ecology, geology, and meteorology and atmospheric sciences. It is important to note that these research areas are based on individual records in Web of Science, rather than authors or journals more generally.

These results were further narrowed to include only the more highly cited publications in each field. After sorting records by research area, the top 10 percent of publication citation counts was identified for each publication year. This mitigated the effects of different citation practices by different research areas, and the higher numbers of citations expected for earlier publication years. For those instances where many publications from a given research area and publication year had the same citation count, the number of publications in the top ten percent was rounded to include only those records with the higher citation count. Table 4 shows (in column A) the number of publications in the top ten percent of citations returned by area for a preliminary search done in November 2015.

Next, a list of distinct authors was identified from these more highly cited publications in each research area. For example, the economics and business search returned 643 distinct authors from the highly cited publications in that area, while the meteorology and atmospheric sciences search returned 8,932 distinct authors. (The number of distinct authors is in column B of the table, and the number of authors per highly cited publication is in column C.) For each author, we calculated a total citation count from this universe of highly cited climate change research papers, over the ten years for this set of publications. For example, Author A might have had a publication in 2009 with 10 citations and another in 2011 with

5 citations, for a total of 15 cites. Note that this is done for all authors in each field.

Next, the lists of authors in each field were narrowed down based on the average number of authors per highly cited publication in that field. This is done because in some fields (e.g., geology) the authors listed on a paper might include everyone in the lab or in any way connected with the research, while in other fields (e.g., economics) only direct (or primary) contributors are included as authors. We want the percentage of authors in each research area to match the percentage of highly cited publications in that area. To do this we identify the research area with the smallest number of authors per publication, and pare down the list of authors in the other areas to match this number, retaining those authors with the most citations. For example, as shown in Table 4, business and economics had the smallest number of authors per publication (2.50). Thus we retained only 47% (i.e., 2.50/5.34) of the 1,506 authors in agriculture, keeping the 705 authors with the largest numbers of citations, and likewise for the other research areas. The adjusted numbers of authors are shown in column D of the table.

With this adjustment, the percentage of authors in each research area (relative to the total number of authors across all five research areas) will match the percentage of highly cited publications in that area, as shown in columns E and F of Table 4.[11]

5.2 The Questionnaire.

Some respondents are likely to find the information that I am after somewhat complex, so the questionnaire must be as clear as possible, and must avoid potential biases. When listing possible outcomes, I begin with "mild" outcomes (e.g., a GDP reduction of 2%) and then move to more serious outcomes.[12] Also, for every question, the respondent will have the option of skipping any question that he/she cannot or prefers not to answer. The questionnaire is shown below.

- **Introduction**: The purpose of this survey is to estimate the social cost of carbon (SCC), an important input to the design of climate policy. Experts were identified

[11] Another way to do the adjustment, which yields the same answers, is as follows. For each research area $i = 1$ to 5, we take the total number of publications in that area identified by Web of Science over the 10 years. Call this P_i. We then calculate the fraction of publications for this research area relative to the total number of publications across all research areas, i.e., $r_i = P_i / \sum_{j=1}^{5} P_j$. Let A_T be the total number of authors across all 5 areas, as identified by citations. Then the adjusted number of authors in research area i is just $N_i = r_i A_T$. Thus we retain the N_i most highly cited authors in research area i.

[12] Morgan (2014) has argued that it is preferable to first ask about the probabilities of extreme outcomes (e.g., a 50-percent or more reduction in GDP) and then the less extreme outcomes, but when testing the questionnaire, I found that people then had more trouble thinking about probabilities.

based on highly cited publications over the past ten years, and include climate scientists, economists, and other individuals who have worked on climate policy. Your identity and the identities of other respondents will be kept confidential; only the overall results of the survey will be published.

This questionnaire should take about 10 minutes to complete. You can skip any questions that you cannot answer, or prefer not to answer. For some questions, we ask how confident you are in your response. Before proceeding, please read the background information below.

- **Background Information**: The questions deal with the possible impact of climate change over the next 50 years and beyond, and the reductions in greenhouse gas (GHG) emissions needed to limit that impact. "Impact" and "emission reductions" should be understood as follows:

  – **Impact**: This is measured as a climate-induced reduction in GDP, broadly defined, relative to what it would be without climate change. Please assume that *without* climate change, world per capita real GDP will continue to grow at a rate of about 2% per year. Climate change, however, could cause floods and other natural disasters, reduce agricultural output, reduce labor productivity, and have other direct effects that would reduce GDP. Climate change might also have indirect effects, such as ecosystem destruction, social unrest, and increased rates of morbidity and mortality that could further reduce future GDP. At issue is *how much lower* GDP might be in the future as a result of climate change, relative to what it would be without climate change. Is the reduction in GDP likely to be only a few percent, or more than 20 percent (an outcome that some economists would consider "catastrophic")? We need your help in assessing this question.

  – **Emission Reductions**: While it may be impossible to avoid *any* future impact of climate change, by reducing the growth of GHG emissions we might avoid a very large impact.

    The average annual growth rate of world GHG emissions over the past 25 years was about 3%, but most of that growth was from Asia. (For the U.S. and Europe, the growth rate of emissions was close to zero.) Some countries have already taken steps to reduce emissions, so under "business as usual" (BAU), i.e., if *no additional steps* are taken to reduce emissions, that growth rate might fall to about 2%. However, many experts believe that the growth rate of emissions must fall further beyond this BAU scenario to avoid a large impact of climate change. We need your help assessing what growth rate of emissions (negative or positive) is needed to avoid this large impact.

- **Question 1**: Under BAU (i.e., no additional steps are taken to reduce emissions), what is your best estimate of the average growth rate of world GHG emissions over the next 50 years? (You might believe that the growth rate will change over time; we want your estimate of the *average* growth rate over the next 50 years under BAU.) Also, on a scale of 1 to 5, how much confidence do you have in your answer (with 5 = very confident)?

Average emissions growth rate under BAU:

Confidence in answer:

- **Question 2**: If no additional steps are taken to reduce the growth rate of GHG emissions, what is the *most likely* climate-caused reduction in world GDP that we will witness in 50 years? In other words, how much lower (in percentage terms) will world GDP be in 2066 compared to what it would be if there were *no* climate change? (Include both direct and indirect effects of climate change in your assessment.)

  Most likely percentage reduction in GDP in 2066:

- **Question 3**: Again, suppose no additional steps are taken to reduce the growth rate of GHG emissions. What is the probability that 50 years from now, climate change will cause a reduction in world GDP of *at least 2 percent*? (In other words, because of climate change, GDP will be at least 2 percent lower than it would have been with no climate change.) What is the probability that climate change will cause a reduction in world GDP of at least 5 percent? At least 10 percent? At least 20 percent? At least 50 percent? (To put these numbers in context, during the Great Depression U.S. GDP fell 25 percent, and at the end of World War II Japan's GDP fell more than 50 percent.) Please express each answer as a probability between 0 and 1. Also, on a scale of 1 to 5, how much confidence do you have in your answers (with 5 = very confident)?

  Probability of 2% or greater reduction in GDP:

  Probability of 5% or greater reduction in GDP:

  Probability of 10% or greater reduction in GDP:

  Probability of 20% or greater reduction in GDP:

  Probability of 50% or greater reduction in GDP:

  Confidence in answers:

- **Question 4**: Now think about the far-distant future — the middle of the next century. If no additional steps are taken to reduce the growth rate of GHG emissions, what is the *most likely* climate-caused reduction in world GDP that we will witness in *the year 2150*? In other words, how much lower (in percentage terms) will world GDP be in 2150 compared to what it would be if there were *no* climate change?

  Most likely percentage reduction in GDP in 2150:

- **Question 5**: Return to the 50-year time horizon, and the possibility that under BAU climate change will cause a reduction in GDP of at least 20 percent (a reduction that might be considered "catastrophic"). In Question 1, we asked for your best estimate of the average growth rate of GHG emissions over the next 50 years under BAU. What is the average annual growth rate of GHG emissions that would be needed to prevent a climate-induced reduction of world GDP of 20 percent or more? (By "prevent," we mean reduce the probability to near zero.) This value might be a positive number, corresponding to slowed growth of emissions, or a negative number corresponding to annual reductions in emissions. Also, on a scale of 1 to 5, how much confidence do you have in your answer (with 5 = very confident)?

Average emissions growth rate needed to prevent a 20% or greater reduction in GDP in 50 years:

Confidence in answer:

- **Question 6**: What is the discount rate that should be used to evaluate future costs and benefits from GHG abatement? (Please provide a *single* discount rate.)

  Discount rate:

- **Question 7**: We would like to learn more about your area of expertise. Is your expertise primarily in climate science (e.g., how accumulating GHG emissions can affect climate), primarily in economics (e.g., how climate change can directly or indirectly affect the economy, costs of abatement, policy design, etc.), or in both?

  Expertise primarily in climate science, primarily in economics, or both:

5.3 Example: 11 Experts.

As a preliminary test, this questionnaire was given to 20 economists and climate scientists, 11 of whom responded. Their answers are summarized in Table 5. Although this sample is small, it can help to illustrate how we can obtain parameter estimates for the three distributions for ϕ, as well as the range of responses we might expect from the full survey. Note that across the 11 respondents, there is general agreement over the growth rate of emissions under BAU (m_0), as well as the likely impact on GDP 50 years from now ($\bar{z}_1$). But opinions regarding the probabilities of alternative outcomes, and opinions regarding the likely impact in 2150, vary widely.

Figure 1 shows the least-squares fit of the gamma, generalized Pareto, and lognormal cumulative distribution functions to the 11 responses to Question 3. Of the three distributions, the Pareto has the highest corrected R^2 (0.567), so I will use that to calculate the SCC. The estimated parameters were $\hat{\alpha} = 29.31$, $\hat{\theta} = -1.470$, and $\hat{k} = 1.633 \times 10^5$. Note that the distribution holds for $\phi \geq \theta + k^{1/\alpha} = 0.036$, i.e., the estimated coefficients imply there is zero probability that ϕ is less than .036. Also note that the very large estimated value of α ($\hat{\alpha} = 29.31$) means that we are working with a distribution that is quite thin-tailed.[13]

[13] This is another illustration of why a fat-tailed outcome distribution is neither necessary nor sufficient to yield a large average outcome, and large SCC.

Table 5: RESPONSES FROM 11 EXPERTS.

Expert	Q1 (m_0)	Q2 ($\bar{z}_1$)	Q3 $\geq 2\%$	$\geq 5\%$	$\geq 10\%$	$\geq 20\%$	$\geq 50\%$	Q4 ($\bar{z}_2$)	Q5 (m_1)	Q6 (R)
1	.02	.04	.60	.20	.05	.01	.001	.10	0.00	.025
2	.03	.06	.59	.48	.35	.20	.04	.33	$-.03$	.0225
3	.02	.08	.90	.50	.05	.01	.00001	.33	$-.04$	.031
4	.02	.05	.80	.30	.05	.02	0.0	.15	0.00	.010
5	.02	.03	.95	.25	.06	.02	.002	.15	0.00	.025
6	.01	.04	.81	.38	.11	.02	0.0	.18	$-.01$	.0229
7	.02	.09	.90	.85	.35	.20	.10	.65	0.00	.020
8	.01	.02	.40	.15	.05	.02	.01	.10	.01	.020
9	.02	.06	.90	.70	.40	.10	.03	.15	0.00	.025
10	.01	.01	.05	.01	.005	.0005	.00001	.05	$-.01$	.020
11	.02	.04	.60	.20	.05	.02	.01	.08	$-.01$	.040
Avg.	.020	.047	.682	.365	.139	.056	.018	.21	$-.010$	.0238

Note: Questionnaire was given to 20 economists and climate scientists, and 11 responded, 10 stating that primary expertise is in economics, and one in climate science.

I calculate a social cost of carbon using this distribution together with the average expert opinion for BAU growth rate of emissions ($m_0 = .020$), the growth rate of emissions needed to eliminate outcomes of $z_1 \geq .20$ ($m_1 = -.010$), and the discount rate ($R = .0238$). I also need a value for β, but the average response for $\bar{z}_1$ and $\bar{z}_2$ (.047 and .210, respectively) imply that $\beta < 0$, so I constrain β to be .005. These numbers, along with the estimated Pareto distribution, yield a value for the SCC of \$82.07 per metric ton.

6 Concluding Remarks.

The estimate of the SCC shown above (\$82.07 per metric ton) is more than twice as large as the most recent estimate by the Interagency Working Group (\$39). The calculations and result shown above, however, are based on the opinions of only 11 individuals, and are meant simply to illustrate how my approach works, and the kinds of results it can yield. The next step will be to elicit the opinions of several thousand experts.

My approach to estimating the SCC has advantages and disadvantages. Its focus on more extreme outcomes addresses what really matters for the SCC, and because of their reliance on IAMs and "most likely" scenarios, is missing from the calculations performed by the Interagency Working Group. Avoiding the use of one or more IAMs is another

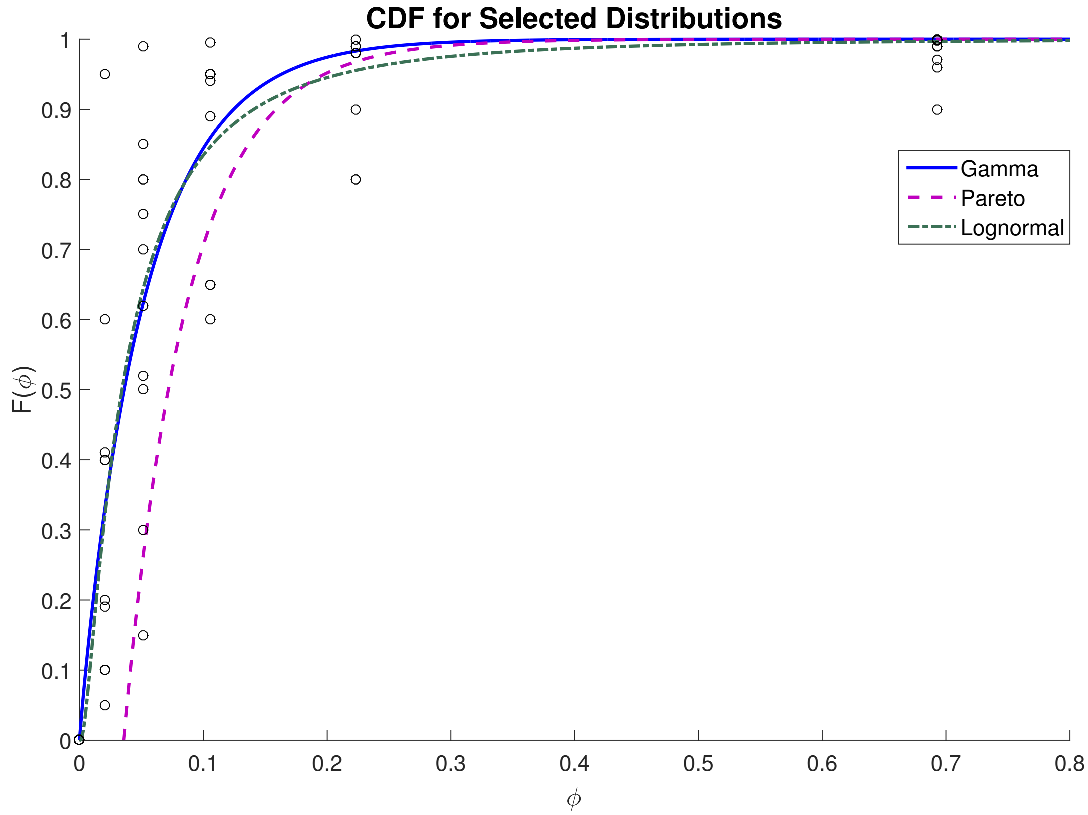

Figure 1: Three Cumulative Distributions, Least-Squares Fit to Outcome Probabilities for 11 Experts in Table 5.

advantage. IAMs hide the extent of our lack of knowledge, and creates a veneer of scientific legitimacy that suggests we know more than we do. The use of expert elicitation is simple and transparent, and summarizes the views of researchers who have studied climate change and its impact.

I calculate an average SCC, not a marginal SCC, which is how environmental economists usually measure the social cost of a pollutant. (Expert opinion cannot be used to determine the impact over the next century of emitting one extra ton of CO_2 today.) As a guide for policy, however, the marginal SCC is of limited use. It can tell us what *today's* carbon tax should be, assuming that total emissions are on an optimal trajectory, but it will change from year to year. The average SCC provides a guideline for policy over an extended period of time, which can be more useful, especially given the difficult and protracted process for actually agreeing on a climate policy. Finally, the average SCC is much less sensitive to the choice of discount rate than is the marginal SCC.

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