Vol. 5, 2011-21 | December 20, 2011 | http://dx.doi.org/10.5018/economics-ejournal.ja.2011-21

Risk Premia and the Social Cost of Carbon: A Review

Carolyn Kousky
Resources for the Future
Robert E. Kopp
U.S. Department of Energy and American Association for the Advancement of Science
Roger Cooke
Resources for the Future and Delft University of Technology

Abstract Reducing greenhouse gas emissions not only lowers expected damages from climate change but also reduces the risk of catastrophic impacts. However, estimates of the social cost of carbon, which measures the marginal value of carbon dioxide abatement, often do not capture this risk reduction benefit. Risk-averse individuals are willing to pay a risk premium, an additional amount beyond the difference in expected damages, to reduce risks. The authors review methods used and estimates obtained for calculating a risk premium to be included in the social cost of carbon. While more research is needed in this area, work to date suggests a positive, and potentially substantial, risk premium on the social cost of carbon is warranted.

Special Issue
The Social Cost of Carbon

JEL Q54
Keywords Climate change; social cost of carbon; risk premium

Correspondence Carolyn Kousky, Resources for the Future, 1616 P Street NW, Washington DC, 20036, USA, e-mail: kousky@rff.org

Citation Carolyn Kousky, Robert E. Kopp, and Roger Cooke (2011). Risk Premia and the Scoial Cost of Carbon: A Review. *Economics: The Open-Access, Open-Assessment E-Journal*, Vol. 5, 2011-21. http://dx.doi.org/10.5018/economics-ejournal.ja.2011-21

1 Introduction

The social cost of carbon (SCC) monetizes the climatic benefits associated with reducing carbon dioxide emissions when such reductions are marginal to total global emissions. In early 2010, the United States government published estimates of the SCC for use in regulatory cost-benefit analysis. These estimates, intended to capture the climatic benefits of regulations that reduce carbon emissions, are based on the expected damages associated with an extra ton of emissions (Interagency Working Group on Social Cost of Carbon 2010).

Growing attention has been paid in recent years, however, to the possibility that climate change could lead, with uncertain probability, to catastrophic impacts. Reducing a ton of emissions not only lowers expected damages but also lowers the probability that catastrophic damages occur. Individuals are generally thought to be risk-averse with respect to low-probability/high-consequence events.[1] This means they would be willing to pay more than the expected reduction in damages to lower the probability of a catastrophe. The SCC should then also include an estimate of the risk reduction benefits of abatement.[2] We will refer to the extra amount on the SCC above expected damages that reflects the willingness-to-pay (WTP) for a reduction in risk as the "risk premium" (RP).

This paper reviews the literature on adding a RP to the SCC. There are very few papers that actually calculate such a premium explicitly, although there are some that implicitly include a RP in their estimates or suggest methods that could be used to do so. Our specific focus here is on analysis of marginal changes in emissions, but we also review papers that estimate a "global" RP, or the extra WTP for worldwide abatement. The work done to date can be divided into three approaches for calculating a RP: using expected utility (EU) theory to calculate a dollar value for the RP, conceptualizing the RP as an alteration to the discount

---

1 For instance, homeowners routinely purchase insurance that is priced substantially above the expected annual loss.

2 While the Office of Management and Budget (OMB)'s Circular A-4 states that risk neutrality should be the default for government projects, Newbold and Daigneault (2010) argue that risk aversion makes more sense for climate change since the potential impacts are global, damages could be very large, and correlation among risks undermines any risk sharing arrangement. OMB guidance notes that risk neutrality "is appropriate as long as society is 'risk neutral' with respect to the regulatory alternatives" and permits alternate assumptions about risk aversion where reasonable grounds for such assumptions exist (Office of Management and Budget 2003).

rate, or by giving extra weight in decision making to worst case scenarios. We provide more detail on all three approaches in this paper. Contrary to some theoretical arguments that a RP is not warranted or would be so negligible as to be not worth consideration, the work in this small literature to date suggests that the RP on the SCC could be significant. Still, there is much more research that needs to be done on this topic.

In Section 2, we first introduce the concept of a risk premium in more detail. We then turn in Section 3 to a discussion of the theoretical work on risk premiums related to climate abatement decisions, including a discussion of two key features of a RP calculation: one, specifying climate damages and two, including uncertainty and adopting a risk-averse utility function. Section 4 discusses the three methods used to date to examine risk premia and summarizes the findings from each. We conclude in Section 5 with a discussion of the implications of the RP research we review and directions for future research.

2 Defining a Risk Premium

The SCC is an estimate of the present value of damages avoided from a marginal reduction in carbon emissions. It monetizes the global economic damage caused through enhanced climate change from emitting a ton of carbon. It is usually estimated using integrated assessment models (IAMs), which jointly model the climate and the economy.[3] It is calculated for a given year as the change in expected welfare over a unit change in emissions, normalized with respect to a welfare-equivalent change in consumption. Estimates are presented as dollars per metric ton of carbon or of carbon dioxide.[4] When emissions are reduced by a ton, not only do expected damages decrease, but the “fat tail” of low-probability, high-impact damages thins. Risk-averse individuals are willing to pay for this reduction in risk under many conditions. Indeed, risk-averse individuals will pay for a mean

[3] There are many assumptions built into the IAMs. There has been a substantial amount of work on investigating these and exploring their implications for the SCC. We put aside these issues in this current paper to focus on the issue of a risk premium. For a broader discussion, see Kopp and Mignone (this issue).

[4] SCC values per metric ton carbon dioxide are equal to SCC values per metric ton carbon times the ratio of the atomic mass of carbon to the molecular mass of carbon dioxide (12/44).

preserving reduction in the variance of losses. With abatement, we reduce both the mean and the variance of losses.

We use the term "risk premium" (RP) to refer to the maximum WTP for the reduction in risk. It is the amount beyond the reduction in the expected value that a risk-averse individual would be willing to pay to reduce a risk. A RP is defined with reference to a risk-averse utility function, $u(.)$, which we take here to simply be over consumption. As an illustration, let c be total consumption without a climate catastrophe, d be damages from a climate catastrophe, p_0 be the probability of a catastrophe with business-as-usual (BAU) emissions, and ($p_0 - \Delta$) be the probability of catastrophe with marginally lower emissions. The individual will be willing to pay at least expected damages for the reduction in risk associated with lowering the probability of damages by Δ. This amount is $d*\Delta$. The RP is the additional amount beyond expected damages they would pay and is defined as:

$$p_0 * u(c-d) + (1-p_0) * u(c) = \qquad (1)$$
$$(p_0 - \Delta) * u(c - (d*\Delta) - RP(\Delta)) + (1 - (p_0 - \Delta)) * u(c - (d*\Delta) - RP(\Delta)).$$

Under this definition, the RP is calculated in dollars. If a utility function is assumed, then the RP could be calculated from this definition (sufficiently modified to include more than two states of the world).

Individuals pay risk premia routinely when purchasing insurance or financial assets. These decisions provide two specific types of WTP to reduce risk that are relevant for our discussion, since a number of climate economics papers use the analogy of insurance and/or draw heavily on financial models, particularly asset pricing theory, to address risk and uncertainty related to climate change. In insurance, the term "risk premium" refers to the amount by which an annual insurance premium exceeds the expected annual costs. With an insurance policy, damages are reimbursed but the probability is not modified and so the RP is a WTP to lower damages in the disaster state of the world. Fully insuring equalizes wealth in the two states of the world with and without a disaster. Consumers would pay the expected damages for this policy and an additional amount specified by the RP. Modifying equation (1) for the particular case of fully insuring all damages gives:

$$p * u(c-d) + (1-p) * u(c) = u(c - (p*d) - RP(d)). \qquad (2)$$

Again, the RP is measured in dollars.

In finance, the RP is the amount added to a risk-free investment to make expected returns equal a risky investment. In this case, the RP is a rate of return. The expected return of a risky investment, r_r, is equal to the rate of return for a safe asset, r_s, plus some risk premium:

$$r_{r=} r_s + RP. \quad (3)$$

While (3) looks like it is of a decidedly different form than equations (1) and (2), note that both (1) and (2) equate the expected utility of a risky position with the expected utility of a less risky position, which is achieved by paying a RP. If we were to examine the utility associated with the rates of return of the investments, equation (3) is also exactly of this form, but the RP is a rate, not a dollar value.

These equations suggest two ways to formulate calculation of a RP for climate change abatement. The RP can be calculated specifically through the utility function as a payment that is decremented from consumption (or wealth) as in equations (1) and (2); alternatively, it can be calculated through rates of return—or discounting—as in equation (3) (more on this in Section 4). The former approach conceptualizes abatement as a type of hazard mitigation investment, while the latter approach considers abatement as a type of investment to be added to the portfolio of investments being held by society.

Some authors have argued that despite discussion of "risk" premia, with climate change catastrophes we are in a situation of Knightian uncertainty as opposed to risk. Research suggests that in cases of ambiguity, where we are uncertain of the probabilities, individuals might command an ambiguity premium (Viscusi and Chesson 1999). This has also been found to be the case with insurance companies (Kunreuther and Hogarth 1992). If governmental policy should reflect these preferences, it suggests an even higher WTP to reduce climate catastrophe risk than would be found in the risk premium calculations and would be a "shadow ambiguity premium" on the SCC (Hennlock 2009). This premium could be calculated through the discount rate as well, such that when the growth rate is uncertain, there is both a risk premium and an ambiguity premium correction to the social discount rate (Millner et al. 2010).

3 Theoretical Background

Many authors have discussed the concept of a risk premium in theory without attempting to estimate the value of the RP. These theoretical discussions are briefly reviewed here. They suggest that there are two components of climate models that will disproportionately impact RP estimates: how climate damages are modeled, and how uncertainty and risk aversion are treated. Both of these are discussed subsequently.

3.1 Is a High Risk Premium Warranted?

Several authors have speculated about whether a RP should be added to the SCC and, if so, what its likely magnitude would be. Mendelsohn (2008) notes that, since uncertainty about the damages associated with an extra ton of emissions in the very near term is low and on a per capita basis "quite small," perhaps no RP should be applied to current emissions. On the other hand, Tol (2008) notes that, given the great uncertainty surrounding climate change impacts, a RP is warranted. Yohe and Tol (2008) argue that, while the extent of the RP to be added to the SCC is uncertain, "it should be clear that no reasonable person would argue that this premium should be zero" (p. 237), and guess that an estimate of 50% of current estimates is "not out of the question" (p. 237). None of these authors present calculations to support their estimates.

One of the most detailed discussions of whether there should be a risk premium on the SCC is given by Nordhaus (2007). He draws on the consumption capital asset pricing model (CCAPM) to state that there will be a positive risk premium if damages occur when the marginal utility of consumption is high, i.e., when society is relatively poor. To evaluate the relationship between consumption and climate damages, he conducts a 100-sample Monte Carlo analysis using his integrated assessment model, DICE. In these samples, he draws from normal distributions representing uncertainty in the productivity growth rate, climate sensitivity, the coefficient of the quadratic damage function, and five other socio-economic and physical factors. He concludes that high-temperature outcomes are positively correlated with consumption. Because the largest damages occur when society is wealthy, this indicates a negative risk premium. He suggests the intuitive idea that if climate damages occur when an individual is rich and has four mansions, but climate change damages one of them, that individual wouldn't want to shift to a state with no damages, but in which he lives in a cave.

However, Nordhaus' analysis, which is based on normal distributions and is dominated by uncertainty in productivity growth, neglects climate catastrophes that could generate low consumption levels in high warming states of the world. It is this possibility that worries authors investigating risk premia. For example, projected levels of warming could lead to serious national security concerns, and could be a threat multiplier for instability in some regions (e.g., CNA Corporation 2007). Warming exceeding 7°C would even directly render increasingly large portions of currently inhabited regions uninhabitable (Sherwood and Huber 2010).

3.2 Damage Functions

This discussion suggests that how damage functions in IAMs treat high temperature states of the world is critical to understanding whether and what magnitude of a RP should be added to the SCC. To calculate an accurate RP, the full range of downside risk must be included in the models. Catastrophic damages can result from large scale impacts associated with accumulated gradual environmental changes or associated with abrupt changes (Dietz et al. 2007). In addition, some Earth system tipping point behaviors can generate positive feedbacks that accelerate and amplify these damages. These high-damage states of the world may be associated with high WTP to buy down the risk.

The notion of catastrophic impacts has been addressed in IAMs for nearly two decades. For early examinations of the issue, see, for example, Nordhaus (1994); Yohe (1996); and Roughgarden and Schneider (1999). Damages from high temperature scenarios have been modeled in various ways. Some authors add extra factors to the damage function for high-temperature scenarios, perhaps in a stochastic fashion (e.g., Gjerde et al. 1999). Azar and Lindgren (2003) use DICE, a commonly used IAM developed by William Nordhaus (Nordhaus 2008), but add a low probability state that has catastrophic damages. Other authors have tried to model specific threshold responses, a classic one being shutdown of the Atlantic Meridional Overturning Circulation (AMOC), for example, by defining an emissions threshold that when crossed leads to higher damages (e.g., McInerney and Keller 2008). The extra damages once a threshold is crossed could also be probabilistic (e.g., McInerney et al. forthcoming). Some other authors, such as

Ceronsky et al. (2005), attempt to model particular climate change scenarios that could generate high damages. Finally, many authors have tried to alter the base damage function in IAMs to create a function that generates higher damages for higher temperature levels. For instance, some attention has focused on the exponent used in the damage function in DICE (e.g., Ackerman et al. 2009). Mastrandrea and Schneider (2001) add a term to the exponent in the DICE damage function whose value is determined by a climate model that simulates AMOC collapse.

3.3 Modeling Uncertainty and Risk Aversion

In addition to including potential catastrophic impacts from climate change, IAMs must be able to address uncertainty explicitly in order to calculate a RP and must use a risk-averse utility function. As Dietz et al. (2007) note, to properly account for risk aversion, the discounted utility from each Monte Carlo draw—each possible outcome of climate change—must be calculated and then weighted by its probability of occurring. Calculating expected consumption instead of expected utility can understate risks (Dietz et al. 2007).

The standard CRRA utility function is used in most climate change economics modeling. With c denoting consumption and η the coefficient of relative risk aversion, it is:

$$U = \frac{c^{1-\eta}}{(1-\eta)}, \text{ for } \eta\neq 1; \; U = \ln(c), \text{ for } \eta=1. \qquad (4)$$

In many IAMs, utility is summed over individuals (generally assuming individuals have identical preferences) and time and discounted back to the present to calculate social welfare.[5]

[5] It should be noted that if individuals in a population have utility functions of the form (4), then the sum of these utility functions will not be of this form. The consequences of using a proxy CRAA utility with an average value of η and multiplying by the population, as opposed to summing the individual utilities, can be profound. Dispersion in marginal utility of consumption across a population is largely responsible for the difference between the expected SCC and the 'certainty-equivalent SCC' described by Newbold et al. (2010).

Assuming a CRRA utility function, the parameter η, which governs the curvature of the utility function, gives an indication of aversion to risk, as well as preferences over intertemporal substitution and intragenerational inequality. These need not be the same, however. Sælen et al. (2009) find that correlations among these three sets of preferences are weak and suggests that models that disentangle these attitudes would be worth pursing further. More relevant for risk premium calculations, the authors find high levels of risk aversion among survey respondents to policies that involve substantial losses, suggesting climate risk premiums could be non-trivial. Nestle (2008) found that risk aversion related to climate damages grows with assets at risk and is greater for damages that are irreversible, generate health impacts, or create a risk of loss of life.

There are several available models that disentangle these effects (Traeger 2009). In the context of climate change, Crost and Traeger (2010) use a recursive dynamic programming model based on DICE and adopt a recursive utility approach to separate out attitudes about intertemporal substitution and risk aversion. Teasing apart these two effects prevents them from being able to use the standard optimal control framework of other IAMs. They find that doing so leads to higher optimal levels of abatement and higher SCC values.

In addition to the tangling of preferences through the CRRA utility function, the DICE IAM (and perhaps other IAMs, such as MERGE) is built around the deterministic Ramsey model (more on this below). Gerst et al. (in prep.) replace the Ramsey model in DICE with the Lucas-Mehra-Prescott model from macro-finance to explicitly address decision-making under uncertainty by separating investments in safe and risky assets. Using historical data to model the growth rate, they find higher levels of risk aversion than typically assumed and that traditional approaches significantly underweight risk reduction benefits associated with abatement. They also conclude that aversion to risk is far more important in driving optimal abatement levels than a thin or fat tailed distribution over climate sensitivity, as long as the welfare function is reasonably bounded from below.

Of course, the debate about the CRRA utility function that has dominated the literature since Weitzman's comment on the Stern Review (Weitzman 2007a) concerns its limit properties, which can be critical in RP calculations as discussed in the next section. As consumption tends toward zero, utility tends toward negative infinity. Discussions in the literature revolve around approaches to bounding the utility function or damages to retain plausible model results (e.g., Dietz 2011a).

4 Methods for Calculating Risk Premia

We now turn to papers that estimate a risk premium. There are very few papers that explicitly calculate the risk reduction value of a marginal change in carbon emissions that could be added to the SCC; more often such a premium may be implicitly included in SCC values. There are also some papers that calculate a risk premium in a global sense of WTP for worldwide abatement. Some of these papers, and others, suggest methods for calculating a marginal RP and they are discussed in this section as well.

Estimation approaches fall into three main groups. The first calculates a RP directly from expected utility. The second addresses risk premia in the context of discounting, as in the financial approach. The third is papers we loosely group as "worst case approaches" that adjust the objective function to take account of risk-aversion regarding worst case climate outcomes. These three approaches and the estimates are discussed in detail in the following sections. It is worth noting that the value of a RP could also be estimated using contingent valuation. As far as we are aware, there have been no attempts to do this.

4.1 Expected Utility Approaches

As discussed in Section 2, the value of a RP could be calculated directly from equation (1). One way to do this is to follow the very simple model of equation (1), assuming two states of the world: climate change and no climate change (or climate disaster and no climate disaster). This is essentially the approach taken by Heal and Kristrom (2002) and Heal (2009). The drawback, of course, is that this is an extremely simplified model. That is also the benefit, however, in that the calculation is very transparent and straightforward. While perhaps too simplistic to use in policymaking, it does provide a good ballpark estimate for what the range of a RP may be.

Heal and Kristrom (2002) and Heal (2009) calculate the willingness of society to pay to avoid the entirety of climate change. They calculate the percentage of income we would be willing to pay using a simple definitional equation. I denotes societal income without climate change (the authors do not appear to let the economy grow over time, which given the discussion earlier, would be an important improvement), climate change occurs in year C, (1-δ) gives the discount rate, climate change drops income to I_j with probability p_j, and x is the WTP to avoid climate risks. This gives the following equation:

$$\sum_{t=1}^{C}\delta^{t-1}(u(I)-u(I-x))=\sum_{t=C+1}^{T}\delta^{t-1}(u(I)-\sum_j p_j u(I_j))\,. \quad (5)$$

For a range of plausible parameter values, they find society may wish to spend between 0.1% to 8.1% of income on avoiding climate change.

Using IAMs, this approach could essentially be scaled up to account for more states of the world. As stated earlier, this requires a risk-averse utility function, which is often assumed to be CRRA in IAMs. This is tied to deterministic Ramsey discounting such that the discount rate r, can be approximated as:

$$r \approx \rho + \eta g, \quad (6)$$

where ρ gives the pure rate of time preference, η is the parameter from the CRRA utility function that governs the concavity of the utility function, and g is the per capita time average growth rate of consumption. The RP calculation is thus linked to the discount rate. This makes the lines between this approach and the one in the next section somewhat blurry. Here, however, the discount rate has not taken account of uncertainty over the growth rate—that is discussed in the next section. Also here, the RP is still seen as a dollar value to add to the SCC while conceptualizing abatement as a hazard reduction measure. In the next section, abatement is conceived of more as another asset that society is holding, the returns from which are uncertain.

As η is a measure of personal risk aversion, varying η when calculating SCC values can give an indication of how the SCC varies with levels of risk aversion. Increasing risk aversion will increase the size of the risk premium. Because of the entangled meanings of η, however, it will also increase discounting of wealthier futures, so the direction of the effect on the SCC is ambiguous. Anthoff et al. (2009) use the IAM FUND to examine how the SCC responds to changes in η when there is uncertainty over climate parameters. The expected social cost of carbon over many Monte Carlo runs at first falls as η increases but then rises, because more emphasis is put on the tails of the distribution. For values of

ρ=1.1% and η=1.5, Anthoff et al. (2009) find that including uncertainty increases the SCC by about \$60/ton C (\$16/ton CO_2) above their deterministic case, but for this central case, the authors do not disentangle the effects of changes in expected wealth and changes in the variance of wealth. By comparison, at ρ=2.0% and η=3.0, they find an expected SCC of over \$20,000/ton C (about \$5,000/ton CO_2). This illustration shows that the level of risk aversion can be a critical driver of SCC and RP values.

Crost and Traeger (2010) add complexity but still essentially adopt an EU framework. They develop a recursive dynamic programming model based on DICE in order to maintain uncertainty in the model run. Uncertainty in their model enters over the climate sensitivity parameter (modeled as a lognormal distribution) and over the damage function. The damage function in DICE multiplies temperature raised to a constant parameter by another constant parameter; Crost and Traeger (2010) model uncertainty over both these parameters. As mentioned earlier, they also reject the common CRRA utility function in order to distinguish risk aversion from other preferences. Comparing their SCC results that explicitly address uncertainty with base runs which draw parameter values and optimize within each run, thus not accounting for uncertainty, gives some sense of the value of a risk premium, even though they do not discuss their findings in this way. The authors find that adding uncertainty adds about \$40/ton C to \$80/ton C (about \$10 to \$20/ton CO_2) to the SCC. In addition to uncertainty, disentangling risk aversion in the utility function also increases SCC values by 70% at the beginning of the century and 25% at the end of the century.

Gerst et al. (2010) use a dynamic stochastic general equilibrium model based on DICE. They model uncertainty over population growth, total factor productivity growth, the change in carbon intensity, climate sensitivity, carbon cycle mass transfer, damages from climate change, and abatement costs. They run their stochastic model with three different abatement scenarios and compare these results to results using "best guess" values of the parameters. Using best-guess values underestimates damages for all the scenarios. The authors do not offer SCC values with or without a RP, but such values could be calculated using their approach. Instead, they examine total social welfare from the different scenarios. They find that ignoring uncertainty leads to an underestimation of damages. With uncertainty, highest social welfare is obtained in the scenario where abatement rises to 100% in 2100. When abatement is based on Nordhaus (2008) results, rising from 10% in 2010 to 100% in 2250, it provides greater welfare than BAU but not as much as the complete abatement by 2100 scenario. When the model is run deterministically with best-guess values and for a higher return on capital of 6%, the Nordhaus scenario becomes the one offering the highest social welfare.

Newbold and Daigneault (2009) model consumption as growing at a constant rate until sometime at which there is a shock that results in the loss of capital. They examine damages with two sigmoidal functions. Using this simple model, they ask: "what is the maximum fractional reduction in consumption, now and forever, that society would be willing to sacrifice to reduce the probability of future temperature changes" from the baseline? In order to estimate a risk premium, Newbold and Daigneault compare their risk-adjusted estimate of benefits with the utility of expected temperature changes.

Newbold and Daigneault assume parameter values to make their comparisons. For a 3°C temperature increase, they assume loss of 2.5% of GDP; for 10°C, they assume 50% loss of GDP. They find their "risk-adjusted WTP" is 15–20 times higher than the deterministic WTP when they use a distribution for climate sensitivity based on averaging previous studies. When they use a tighter distribution on the climate sensitivity, the risk premium is negligible, highlighting the sensitivity of risk premium results to how the uncertainty is specified. They also examine their results as η changes. Increasing η decreases WTP up until a point and then it starts to increase WTP. This is also found by Anthoff et al. (2009) as discussed earlier. This is because with uncertainty, even if future generations will on average be wealthier, there is a chance they could be quite poor. When this probability is high enough, a higher CRRA will lead to a higher WTP to prevent the catastrophic outcome. Thus, when the various meanings of η, as discussed earlier, are not disentangled, aversion to inequality effect can dominate in situations of low uncertainty and aversion to risk can dominate in situations of high uncertainty.

Newbold and Daigneault then turn to DICE to see if their results hold with a more complex model. They compare BAU with two policies of more aggressive and less aggressive abatement. As in the stylized model, risk-adjusted WTP is generally higher than deterministic WTP. Like Nordhaus (2007), they find a negative risk premium for the less aggressive abatement policy, which they attribute to the "less severe" damage function used in DICE, again highlighting the importance of how catastrophic damages are modeled. In particular, the damage function is not everywhere convex. There is a range where an increase in variance makes the risk premium more negative because mass is shifted to where marginal damages are decreasing. A negative risk premium is more likely to emerge the lower the inflection point in the damage function.

4.2 Discounting Approaches

The financial definition of a risk premium discussed earlier shows how viewing abatement as an investment could allow calculation of a RP as a rate of return or change in the discount rate. In the previous section we saw that levels of risk aversion do alter the discount rate, even when growth is not stochastic. The problem with the deterministic Ramsey setting is that there is only one interest rate—r—and as such, it does not address variations in the risk associated with different assets.[6] Expanding the analysis to include different rates of return based on the riskiness of the asset can be done drawing on asset pricing theory, as in Wetizman (2007a). Under the Capital Asset Pricing Model, the return needed on an asset is a function of its correlation with market returns—the risky investment. Let the return on the asset (consider abatement as a type of "asset" that could be invested in) be r_a, let r_s again be the return on a safe asset or the risk-free rate of return, let r_r, be the return on the risky asset (often taken to be the market in finance applications, and we will do that here), and let β be the correlation between the returns from the asset and from the risky asset or the market. Then:

$$r_a \approx r_s + \beta(r_r - r_s). \tag{7}$$

Thus, the rate of return and the RP for an asset depend on the asset's correlation with economy-wide returns. This then begs the question: are climate damages, which abatement reduces, correlated, anti-correlated, or uncorrelated with the rest of the economy? Most IAMs model damages as a pure production

6 Apart from the discussion here, it is worth mentioning, as Dietz (2011b) observed, that since the discount rate is dependent on consumption growth rates, each Monte Carlo draw should have its own discount rate instead of using exogenous rates as done in the US Social Cost of Carbon for Regulatory Impact Analysis report. Indeed, the flat discount rates are inconsistent with the assumption in the US government analysis that per capita GDP growth will decline to zero by 2300.

externality and damages are thus positively correlated with the overall economy; abatement pays off more when the economy is also paying off more. There is not necessarily an economic justification for this assumption (Howarth 2003). Climate change can be seen as mostly impacting "outdoor" sectors of the economy (e.g., agriculture and coastal recreation), and these could impact utility directly (Sterner and Persson 2008), suggesting that the correlation is greater than zero but less than one (Weitzman 2007a). If abatement reduces the risk of catastrophes, the correlation with the rest of the economy could even be negative (Brekke and Johansson-Stenman 2008). In this case, abatement reduces the risk of the entire portfolio of society's holdings and thus requires a lower rate of return than even safe investments.

Weitzman (2007a; 2007b) exploits this conceptualization of abatement as a type of investment and links the RP for climate change abatement to the "equity risk premium puzzle" in finance. If we model the per capita growth rate of the economy as a random variable normally distributed with mean μ and variance σ^2, with δ representing the pure rate of time preference, and η the coefficient of relative risk aversion, then the rate of return for a risk-free asset is approximated by:

$$r_s \approx \delta + \eta\mu - \tfrac{1}{2}\eta^2\sigma^2, \qquad (8)$$

and the risk premium for equities (the risky asset in this model) is approximated by:

$$\mathrm{RP} \approx \mathrm{E}[r_e] - r_s = \eta\sigma^2. \qquad (9)$$

The equity premium puzzle is the conundrum that when plausible parameter values are used, it is impossible to explain the large equity premium observed in the market. Weitzman (2007b) resolves this puzzle by positing that there is uncertainty over the growth rate such that it has a fat left tail. (Note that, given this assumption of non-normality, the approximations in equations 8 and 9 no longer hold.) With certain model assumptions, this can imply an infinite risk premium for equities!

Weitzman (2007a; 2009) extends this thinking to the climate change problem. He models the growth rate in consumption as uncertain due to potential climate damages. Using a Bayesian updating framework where the growth rate is unknown but updated based on limited past observations, the posterior distribution for the growth rate is the fat-tailed Student-t. Using this student-t distribution, the expected marginal utility of an extra sure unit of consumption tends to infinity. Even if a somewhat arbitrary bound is used in the model to eliminate the infinity, the model still suggests that concern for possibly catastrophic climate impacts leads to a very large risk premium. Others have argued, though, that if the CRRA utility function is bounded, WTP may be smaller and much more reasonable than a first read of Weitzman (2009) would suggest and could be driven by other factors such as risk aversion and the damage function (Newbold and Daigneault 2009; Pindyck 2010). Still, Weitzman's work points to the fact that there may be conditions under which we are willing to pay quite a bit to avoid a very large downside exposure from climate change.

Dietz (2011a) explores the implications of Weitzman's work by using the IAM PAGE with fat-tailed distributions for the climate sensitivity and damage exponent. Damages are bounded at different levels to avoid the infinite WTP that Weitzman discusses. Bounding damages, keeping the probability of catastrophe small, and assuming that catastrophic damages do not occur until well into the future is enough to make the welfare costs of climate change asymptote, with the value determined by the discount rate and the coefficient of relative risk aversion, η (Dietz 2011a). Dietz (2011a) gets much higher SCC estimates using fat-tailed distributions but the level of risk aversion, as captured by η, is still important. For his BAU run and a pure rate of time preference of 0.1 and η=2, he finds the mean SCC to be \$444/t CO_2 in 2008 US\$. For BAU with a pure rate of time preference of 1.5 and η=3, the mean estimate is \$346/t CO_2.

4.3 Worst Case Approaches

As opposed to explicitly calculating a risk premium, some authors have suggested decision rules that take account of worst-case scenarios more explicitly than simply looking at average damages. McInerney et al. (forthcoming) examine two approaches—limited degree of confidence (LDC) and safety first (SF)—that demonstrate some concern for welfare in the worst-case scenario. The former maximizes a weighted average of expected welfare and welfare in the worst case and the latter maximizes welfare subject to welfare in the worst case remaining above some threshold. With climate change, however, there is no one worst-case scenario and the estimates of worst outcomes are very sensitive to sample size, especially when sampling from fat-tailed distributions. The worst case says nothing about the probability of occurrence or about other undesirable outcomes. To address these concerns, McInerney et al. substitute conditional value-at-risk (CVaR) for the worst-case outcome. Also termed expected shortfall or tail-value-at-risk, CVaR is the expected value of the distribution above a given percentile.

Although McInerney et al. focus on global optimization questions, one can apply their approach in a marginal context to add a RP to the SCC. For instance, McInerney et al.'s limited degree of confidence criterion is based on minimizing the weighted average of expected damages and CVaR. The SCC could be calculated as the marginal of this objective function, i.e., as a weighted average of expected damages and the damages above a given percentile. The weight would be based on the degree of risk aversion society exhibited toward catastrophic climate outcomes, and with appropriate calibration could capture the WTP to reduce the risk of climate catastrophes.

Another related approach that several papers have explored is optimizing decision making under a risk constraint. If we take such risk constraints to implicitly give society's level of risk aversion, then the tax that would be required to get society on the least-cost path that satisfies the constraint could be seen as a SCC with a risk premium included (although not one calculated off of a business-as-usual scenario, as in the US government estimates). Mastrandrea and Schneider (2004) use DICE with different damage functions to examine what carbon taxes keep the probability of crossing into "dangerous anthropogenic interference" (DAI) below certain levels. They find that a carbon tax in 2050 of $150 to $200 per ton of carbon brings the probability of DAI down from about 45% without abatement to close to zero. McInerney and Keller (2008) impose a reliability constraint in DICE to model a decision to lower the odds of collapse of the North Atlantic circulation to an acceptable level. The way they model circulation collapse in the North Atlantic leads them to conclude that reducing the odds of collapse to 1 in 10 requires almost complete decarbonization. Cooke (in prep) infers a probabilistic risk constraint from international agreements. The difference in time discounted damages along the BAU and along an (approximately) optimal path satisfying the risk constraint are a lower bound on WTP to reduce society's risk.[7]

5 Conclusion and Future Directions

While many commentators discuss abatement as a risk management strategy to lower the probability of severe climate damages, relatively few authors have analytically operationalized this framework. One way to do so in a regulatory framework is through the calculation of a risk premium associated with the social cost of carbon. We have reviewed the work on calculating such a premium to date. Several approaches have been taken to including the risk reduction benefits of abatement in SCC values, ranging from deriving a risk premium directly from EU equations, to adjusting the discount rate to account for uncertainty and risk aversion, to placing greater weight on worst-case outcomes. As very few authors pull out RP values to report independently, it is difficult to gauge how these methods compare.

The work across all approaches suggests that risk premia are likely warranted when evaluating abatement options and are not likely to be trivial. Indeed, our review suggests they could actually be very large. This is in part due to risk aversion to catastrophes, which is tangled with other preferences in the standard model, and which some studies suggest may be higher than previously considered. It is also due to the enormous uncertainty over the climate change damage function. Many IAM studies have used a limited set of damage functions. Researchers are now realizing that there are many ways in which scientifically plausible catastrophes can be incorporated into the damage function, and that this can greatly influence the size of the risk premium.

As our review makes clear, there is much more work to do on this topic. Since RP values are dependent on whose preferences are being considered, more

[7] Dietz (2011b) notes that SCC estimates are much more uncertain than estimates of marginal abatement costs, particularly given this deep uncertainty about the damage function. He thus recommends setting a long-run emissions target based on our concerns about catastrophic climate change, since with an unknown potential for catastrophic damages, marginal benefits from climate change are steeply increasing once some threshold is reached, with marginal costs being relatively flat: Weitzman's seminal work thus suggests the use of a quantity instrument.

research on individual risk attitudes toward climate change catastrophes would be useful, as well as whether the commonly used CRRA utility function is appropriate. As other authors have also stated, further work on modeling climate damages is needed from the perspective of risk premia, as well. Uncertainty analysis over not only parameter values of certain damage specifications, but also across different damage models would be useful (see Kopp et al. (2011)) as there is currently no theoretical reasons to assume one functional form is more accurate than another.

Acknowledgements The authors are grateful to Stephen Newbold and Gernot Wagner for helpful comments. This work was supported by the U.S. Department of Energy Office of Policy & International Affairs and the U.S. Climate Change Technology Program. This paper represents the personal views of the authors. It does not reflect the official views or policies of the United States government or any agency thereof, including DOE. REK was supported by an appointment to DOE under the American Association for the Advancement of Science Fellowship Program administered by Oak Ridge Institute for Science and Education.

References

Ackerman, F., E.A. Stanton, and R. Bueno (2009). Fat tails, exponents, and extreme uncertainty: simulating catastrophe in DICE. Stockholm Environment Institute Working Paper WP-US-0901. http://sei-us.org/Publications_PDF/SEI-WorkingPaperUS-0901.pdf

Anthoff, D., R.S.J. Tol, and G.W. Yohe (2009). Risk aversion, time preference, and the social cost of carbon. *Environmental Research Letters* 4. doi:10.1088/1748-9326/4/2/024002. http://iopscience.iop.org/1748-9326/4/2/024002

Azar, C. and K. Lindgren (2003). Catastrophic Events and stochastic cost-benefit analysis of climate change. *Climatic Change* 56(3): 245–255. http://www.springerlink.com/content/u0466411k34v0032/

Brekke, K.A. and O. Johansson-Stenman (2008). The behavioural economics of climate change. *Oxford Review of Economic Policy* 24(2): 280–297. http://oxrep.oxfordjournals.org/content/24/2/280.short

Ceronsky, M., D. Anthoff, C. Hepburn and R. S. J. Tol (2005). Checking the price tag on catastrophe: the social cost of carbon under non-linear climate response. Working Paper FNU-87. Forschungsstelle Nachhaltige Umweltentwicklung, Hamburg. http://www.fnu.zmaw.de/fileadmin/fnu-files/publication/working-papers/catastrophewp.pdf

CNA Corporation (2007). National security and the threat of climate change. The CNA Corporation, Alexandria, Virginia. http://www.cna.org/reports/climate

Crost, B. and C. Traeger (2010). Risk and aversion in the integrated assessment of climate change. CUDARE Working Paper 1104. Department of Agricultural & Resources Economics, UC Berkeley, Berkeley, CA. http://escholarship.org/uc/item/1562s275#page-2

Dietz, S. (2011a). High impact, low probability? an empirical analysis of risk in the economics of climate change. *Climatic Change* 108(3): 519–541. http://ideas.repec.org/a/spr/climat/v108y2011i3p519-541.html

Dietz, S. (2011b). The treatment of risk and uncertainty in the US social cost of carbon for regulatory impact analysis. Centre for Climate Change Economics and Policy Working Paper No. 64. Centre for Climate Change Economics and Policy, University of Leeds and the London School of Economics and Political Science, London, UK.

Dietz, S., C. Hope and N. Patmore (2007). Some economics of 'dangerous' climate change: reflections on the stern review. *Global Environmental Change* 17: 311–325. http://www.mendeley.com/research/some-economics-of-dangerous-climate-change-reflections-on-the-stern-review-1/

Gerst, M.D., R.B. Howarth and M.E. Borsuk (2010). Accounting for the risk of extreme outcomes in an integrated assessment of climate change. *Energy Policy* 38: 4540–4548. http://ideas.repec.org/a/eee/enepol/v38y2010i8p4540-4548.html

Gerst, M.D., R.B. Howarth and M.E. Borsuk (in prep.). Society's aversion to risk justifies aggressive greenhouse gas emissions reduction. Dartmouth College, Hanover, NH. http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CB4QFjAA&url=http%3A%2F%2Fgretha.u-bordeaux4.fr%2Fspip.php%3Faction%3Dacceder_document%26arg%3D718%26cle%3Dbb79b676f737ae68f2715359bd872df3%26file%3Dpdf%252Fgerst_et_al_working_paper.pdf&ei=PKnnTrD6NePx0gHJiZ3_CQ&usg=AFQjCNFtkC_qIVREcJh4AT85Tg44gERM4g

Gjerde, J., S. Grepperud and S. Kverndokk (1999). Optimal climate policy under the possibility of a catastrophe. *Resource and Energy Economics* 21: 289–317. http://ideas.repec.org/a/eee/resene/v21y1999i3-4p289-317.html

Heal, G. (2009). The economics of climate change: a post-stern perspective. *Climatic Change* 96: 275–297. http://www.springerlink.com/content/2866362w164531tg/

Heal, G. and B. Kristrom (2002). Uncertainty and climate change. *Environmental and Resource Economics* 22: 3–39.

Hennlock, M. (2009). Robust control in global warming management: an analytical dynamic integrated assesement. RFF Discussion Paper 09-19. Resources for the Future, Washington, DC, May. http://www.rff.org/documents/RFF-DP-09-19.pdf

Howarth, R.B. (2003). Discounting and uncertainty in climate change policy. *Land Economics* 79(3): 369–381.

Interagency Working Group on Social Cost of Carbon (2010). Social cost of carbon for regulatory impact analysis under executive order 12866. Washington, DC, February.

Kopp, R.E., A. Golub, N.O. Keohane, and C. Ondra (2011). The influence of the specification of climate change damages on the social cost of carbon. Economics Discussion Papers, No 2011-22. http://www.economics-ejournal.org/economics/discussionpapers/2011-22.

Kunreuther, H. and R. M. Hogarth (1992). How does ambiguity affect insurance decisions? In G. Dionne (Ed.), *Contributions to Insurance Economics*. Boston: Kluwer.

Mastrandrea, M. D. and S. H. Schneider (2001). Integrated assessment of abrupt climatic changes *Climate Policy* 1(4): 433–449. http://stephenschneider.stanford.edu/Publications/PDF_Papers/IntegratedAssessment.pdf

Mastrandrea, M.D. and S.H. Schneider (2004). Probabilistic integrated assessment of "dangerous" climate change. *Science* 304(April 23): 571–575. http://www.sciencemag.org/content/304/5670/571.abstract

McInerney, D. and K. Keller (2008). Economically optimal risk reduction strategies in the face of uncertain climate thresholds. *Climatic Change* 91: 29–41. http://www.springerlink.com/content/p238w50423462307/

McInerney, D., R. Lempert and K. Keller (forthcoming). What are robust strategies in the face of uncertain climate threshold responses? *Climatic Change*.

Mendelsohn, R. (2008). Is the Stern Review an economic analysis? *Review of Environmental Economics and Policy* 2(1): 45–60. http://ideas.repec.org/a/oup/renvpo/v2y2008i1p45-60.html

Millner, A., S. Dietz and G. Heal (2010). Ambiguity and climate policy. Centre for Climate Change Economics and Policy, University of Leeds and the London School of Economics and Political Science, London, UK.

Nestle, I. (2008). Evaluation of risk in cost-benefit analysis of climate change. In B. Hansjürgens and R. Antes (Eds.), *Economics and Management of Climate Change:Risks, Mitigation and Adaptation*. New York: Springer. http://www.springerlink.com/content/k48378675111h165/

Newbold, S. and A. Daigneault (2009). Climate response uncertainty and the benefits of greenhouse gas emissions reductions. *Environmental and Resource Economics* 44(3): 351–377. http://ideas.repec.org/a/kap/enreec/v44y2009i3p351-377.html

Newbold, S.C. and A. Daigneault (2010). Uncertainty and the benefits of climate change policies. In J. Gulledge, L. J. Richardson, L. Adkins and S. Seidel (Eds.), *Assessing the Benefits of Avoided Climate Change: Cost-Benefit Analysis and Beyond*. Arlington, VA: Pew Center on Global Climate Change. http://www.pewclimate.org/events/2009/benefitsworkshop

Newbold, S.C., C. Griffiths, C. Moore, A. Wolverton and E. Kopits (2010). The "social cost of carbon" made simple. Working Paper No. 10-07. National Center for Environmental Economics, United States Enviromental Protection Agency, Washington, D.C. http://ideas.repec.org/p/nev/wpaper/wp201007.html

Nordhaus, W. (1994). *Managing the global commons*. Cambridge, MA: MIT Press. http://mitpress.mit.edu/catalog/item/default.asp?ttype=2&tid=7299

Nordhaus, W. (2007). *The challenge of global warming: economic models and environmental policy*. New Haven, CT: Yale University Press. http://nordhaus.econ.yale.edu/dice_mss_072407_all.pdf

Nordhaus, W. (2008). *A question of balance: weighing the options on global warming policies.* New Haven, CT: Yale University Press. http://yalepress.yale.edu/book.asp?isbn=9780300137484

Office of Management and Budget (2003). Circular A-4. Office of Management and Budget, Washington, D.C.

Pindyck, R.S. (2010). Fat tails, thin tails, and climate change policy. NBER Working Paper No. 16353. National Bureau of Economic Research, Cambridge, MA. http://ideas.repec.org/p/nbr/nberwo/16353.html

Roughgarden, T. and S.H. Schneider (1999). Climate change policy: quantifying uncertainties for damages and optimal carbon taxes. *Energy Policy* 27(7): 415–429. http://ideas.repec.org/a/eee/enepol/v27y1999i7p415-429.html

Sælen, H., S. Dietz, C. Hepburn, J. Helgeson, and G. Atkinson (2009). Siblings, Not Triplets: Social Preferences for Risk, Inequality and Time in Discounting Climate Change. *Economics: The Open-Access, Open-Assessment E-Journal*, Vol. 3, 2009-26. http://dx.doi.org/10.5018/economics-ejournal.ja.2009-26

Sherwood, S.C. and M. Huber (2010). An adaptability limit to climate change due to heat stress. *Proceedings of the National Academy of Sciences* 107(21): 9552–9555. http://www.pnas.org/content/107/21/9552

Sterner, T. and U.M. Persson (2008). "An even sterner review: introducing relative prices into the discounting debate. *Review of Environmental Economics and Policy* 2(1): 61–76. http://ideas.repec.org/a/oup/renvpo/v2y2008i1p61-76.html

Tol, R.S.J. (2008). The social cost of carbon: trends, outliers, and catastrophes. *Economics: The Open-Access, Open-Assessment E-Journal*, Vol. 2, 2008-25. http://www.economics-ejournal.org/economics/journalarticles/2008-25

Traeger, C.P. (2009). Recent developments in the intertemporal modeling of uncertainty. *Annual Review of Resource Economics* 1(1): 261–286. http://ideas.repec.org/a/anr/reseco/v1y2009p261-285.html

Viscusi, W.K. and H. Chesson (1999). Hope and fears: the conflicting effects of risk ambiguity. *Theory and Decision* 47: 153–178. http://www.springerlink.com/content/r61m07n271836q05/

Weitzman, M.L. (2007a). A review of the stern review on the economics of climate change. *Journal of Economic Literature* XLV(September): 703–724. http://www.cepe.ethz.ch/education/EnergyPolicy/Weitzman.pdf

Weitzman, M.L. (2007b). Subjective expectations and asset-return puzzles. *The American Economic Review* 97: 1102–1130. http://ideas.repec.org/a/aea/aecrev/v97y2007i4p1102-1130.html

Weitzman, M.L. (2009). On modeling and interpreting the economics of catastrophic climate change. *Review of Economics and Statistics* 91(1): 1–19. http://ideas.repec.org/a/tpr/restat/v91y2009i1p1-19.html

Yohe, G. (1996). Exercises in hedging against extreme consequences of global change and the expected value of information. *Global Environmental Change* 6(2): 87–101.

Yohe, G. and R. Tol (2008). The Stern Review and the economics of climate change: an editorial essay. *Climatic Change* 89(3): 231–240. http://www.springerlink.com/content/d24654n30830l5lw/

Economics
The Open-Access, Open-Assessment E-Journal