Response to Referee Report 1 dp 2011-22
19 September 2011

In the below, the referee's comments are shown in indented italics; our responses are shown in left-justified, unindented text.

> *My comments, which conclude with a discussion of this comparison, are divided into three parts. The first considers context by casting the raw results into the distribution of estimates of the social cost of carbon reported by Tol (2008) in his most recent meta- analysis. The second identifies two places where the modeling structure is not quite standard, and offers some suggestion of how much of a difference they make. The third focuses attention on the comparison of the reference case scenarios to the stabilization alternatives.*

We skip over the referee's first comment, which indicates that our SCC estimates for the first two damage functions are reasonably consistent with previously published values, given their use of a 3% average discount rate, and focus on the referee's second and third comments.

> *2. Two non-standard modeling decisions.*
>
> *These comparisons have to be interpreted carefully for two additional reasons. First of all, Kopp, et al. (2011) use a non-standard representation of the Ramsey discounting rule; i.e., they assume that (their equation (5)):*
>
> $1 + r = (1+\varrho)(1+g)^{\eta}$ *(1)*
>
> *rather than the more traditional representation:*
>
> $1 + r = 1 + \varrho + \eta g$ *(2)*
>
> *from Ramsey (1928). In either formulation, g should represent the rate of growth of per capita consumption and not GDP. Using their 2.03% growth rate assumption, equation (2) would suggest that ϱ = 3%, 0.98%, and 0.16% would be more appropriate for η = 0, 1, respectively - not much of a difference, to be sure.*
>
> *But using an estimate of, say, 1.3% for the growth rate of per capita consumption, the corresponding values for ϱ should be 3%, 1.7%, and 1.18%, respectively - perhaps a significant difference.*

The derivation of equation (1) is given in Kopp & Mignone (2011; Economics Discussion Paper 2011-16), among other places; we briefly repeat here. It follows directly from the assumption in the common IAMs of an isoelastic utility function with constant rate of pure time preference ϱ and coefficient of relative risk aversion η. In such a model, the marginal utility of consumption c at time t is given by

$$u(c,t) = c^{-\eta}/(1+\varrho)^{t}.$$

Assume consumption grows at rate g, such that $c(t) = c_0(1+r)^t$. In equilibrium, the marginal utility of a unit of consumption at time t will equal the marginal utility of a unit of consumption at time $(t + 1)$. Thus,

$$c_0^{-\eta} = (1 + r)[c_0(1+g)]^{-\eta}/(1+\varrho)$$

$$(1 + r) = (1 + \varrho)(1 + g)^{\eta}$$

This expression can be approximated by the referee's equation (2), which is strictly correct (using these definitions of rates) in the limiting case of continuous time. Since IAMs run in discrete time steps, equation (1) above is the correct equation to be using. This is particularly true when picking different decompositions of *r* to generate an century-average discount rate of 3%, since in this case the relevant time step is 100 years.

Alternatively, the reviewer's equation 2 is correct if rates are defined in terms of natural exponents, such that:

$$u(c,t) = c^{-\eta}/\exp(\varrho' t).$$

$$c_0^{-\eta} = \exp(r' t)[c_0 \exp(g' t)]^{-\eta}/\exp(\varrho' t)$$

$$r' = \varrho' + g' \eta$$

This is the continuous time counterpart to the previous equation. As long as one is consistent in how one defines rates, one can use either formulation, but the numerical values of rates will differ.

As an aside, it is worth noting that neither DICE nor our implementation thereof calculate or employ *r*; it uses an isoelastic utility function with constant rate of pure time preference, and *r* falls naturally out of it. The Ramsey expression is used only to decompose the discount rate.

> *The second source of concern is perhaps more important. Kopp, et al. (2011) do not, for some reason, use the conventional certainty equivalent calculation to estimate the social cost of carbon across the uncertain runs that they employ. Instead, as described in Section 2.3, they use something like:*
> $SCC \equiv \{\Delta EU/\Delta CO2\}/\{\Delta EU/\Delta consumption\}$. *(3)*
>
> *The second term in (3) seems to assume that expected utility can be viewed as a function of average consumption; otherwise how is it consistently defined across multiple states of nature? Of course, expect utility is not a function of expected consumption. It therefore strikes me that something like*
> $SCC \equiv \{\Delta EU/\Delta CO2\}/E\{\Delta U/\Delta consumption\}$ *(4)*
>
> *would have been more appropriate - something, in other words, that would have allowed the diversity of marginal utilities across the range of scenarios to be recognized so that η would reflect aversion to inequality as well as aversion to risk. Anthoff, et al. (2009) produced certainty equivalent SCC estimates from Tol's FUND model assuming a joint distribution for ϱ and η reported by Evans and Sezer (2005). Ignoring both risk aversion and inequality aversion (closest to the ϱ = 3% casehere), they estimate SCC ~$40 per ton of carbon (~$13-16 per ton of CO2 in 2015 with adjustment per Hope (2006)). When uncertainty is viewed through a risk averse lens, only, SCC climbs to ~$120 per tone of carbon (~$40-49 per ton of CO2 adjusted for 2015); and adding aversion to inequality that Kopp, et al. (2011) miss, SCC nearly doubles to approximately $230 per ton of carbon (~$77-93 per ton of CO2 in 2015). Only the last case approaches the SCC values reported for Kopp, et al (2011).*

We agree with the reviewer that expected utility is not a function of expected consumption, and that it would be incorrect to define the social cost of carbon in such terms. We disagree with the reviewer that his equation 3 would define expected utility in such terms.

We define the social cost of carbon as "the change in expected [social] welfare from a unit emission of carbon dioxide in a given year, normalized to change in expected [social] welfare from a unit of consumption in the same year." In this, we follow other authors who have offered explicit definitions and considered alternatives (e.g., Newbold et al., 2011).

Since we are employing a single representative agent model, social welfare (W) is defined as the expectation value of the utility (U) of this agent across states of the world ($W = \mathrm{E}(U(c))$), taking into account that consumption c differs in each state of the world, and so U differs in each state of the world. Note that this is not the same as the alternative definition ($W' = U(\mathrm{E}(c))$), which is what the reviewer suggests in the sentence following equation (3) above.

(Note that, in the previous paragraph, we neglect population change over time, which is incorporated into the model.)

Thus, our definition of the SCC is:

$$\mathrm{d}W/\mathrm{d}(CO2) \;/\; \mathrm{d}W/\mathrm{d}c = \mathrm{d}(\mathrm{E}(U(c)))/\mathrm{d}(CO2) \;/\; \mathrm{d}(\mathrm{E}(U(c)))/\mathrm{d}c;$$

although the reviewer is not employing marginals in his notation, I assume this is identical to his equation 3.

To calculate expected utility, one calculates utility for each state of the world individually (noting that consumption in each state of the world differs) then takes the (probability-weighted) mean across states of the world.

By contrast, we define the 'deterministic SCC' for a given state of the world as

$$\mathrm{d}W'/\mathrm{d}(CO2) \;/\; \mathrm{d}W'/\mathrm{d}c = \mathrm{d}(U(\mathrm{E}(c))/\mathrm{d}(CO2) \;/\; \mathrm{d}(U(\mathrm{E}(c))/\mathrm{d}c.$$

Of course, DICE assumes the entire world is represented by a single representative agent; many other interesting questions -- some addressed by Anthoff et al. (2009) -- arise in a multi-agent model, but they are beyond the scope of our manuscript. (In general, they relate to the issue of whose additional unit of consumption appears in the denominator.)

> *3. The value of stabilization.*
>
> *Turning now to the value of stabilization, Table 1 reports differences between the Kopp, et al. (2011) Tables 3 and 4 (illustrated in Figure 8) as percentages relative to the reference case estimates. It is important, in interpreting the several notable trends that emerge here, to understand that stabilization produces benefits for three reasons. The first is obvious - lower long run temperatures certainly diminish long term impacts and therefore the discounted economically based damage estimates that are reflected in the SCC. The second two are less obvious - stabilization interventions not only reduce the range of uncertainty at any point in time, but also push the full range of potential damages for a point in time along the reference scenarios farther into the future. Both of these forces should work to lower SCC estimates for cases with no-zero risk aversion (at least for estimates generated by*

calculating certainty equivalents); and all three should contribute to reducing SCC for all but the first case wherein risk aversion is taken to be zero.

Table 1 shows the expected direction of change for all of the cases except for the SP, Xc, and Wa damage variants. Explaining exactly why those cases deviate from expectation (especially for case 1 where $\eta = 0$) would be an important addition to the discussion. Nonetheless, note that all of the changes are exaggerated for the last set of damage functions where damages accelerate with temperature.*

Table 1 also shows, as expected, that increases in aversion to risk increase the value of stabilization – except for the the Xi (i = a; b; b; c; and c*) damage variants. Again, why? Without some explanations about these results, the credibility of the damage functions that support these cases must be viewed with some skepticism.*

We respectfully disagree with the reviewer's principal assumptions here. In particular, it is not appropriate to use changes in the social cost of carbon -- which is a marginal value -- to assess the benefits of making a non-marginal shift in emissions pathways. Shifting from a baseline emissions scenario to a stabilization scenario can produce positive social benefits while either increasing or decreasing the SCC. We refer the reader to section 6.2 of Kopp and Mignone (2011), from which we briefly quote here:

> Suppose most climate change damages will be associated with a major Earth system tipping point, and further suppose that baseline emissions push the Earth system well over this tipping point. The … SCC will take into account the effects of gradual climate changes that occur in the post-tipping point world. It will not, however, take into account the damages associated with the tipping point, since the planet crosses the tipping point with or without the emission of a marginal ton. Yet society is willing to pay to avoid those damages, and an additional ton of abatement makes it marginally easier to achieve that goal – a benefit not quantified by the … SCC….

> The SCC is informed by an underlying Pigouvian logic, and the above example highlights the limits of the Pigouvian framework, discussed by Baumol (1972). Imposing a Pigouvian tax equal to the marginal external cost of an economic activity, calculated for a level of the activity corresponding to a maximum of social welfare, will maintain the activity level at the optimum. If the optimal level of an activity is not known a priori, imposing a tax equal to the marginal external cost at the current level of the activity and then updating as the level adjusts will lead to convergence to an optimal value. But (as illustrated in the example above) strong environmental externalities often give rise to non-convex social welfare functions with multiple local maxima, and there is no guarantee that this trial-and-error process will converge to the global maximum.

As we observe in the manuscript, some of the damage functions we employ give rise (at least for some parameter values) the non-convexities discussed by Baumol (1972). As we note: "With these damage functions, emissions and growing wealth in the reference scenario are sufficient to carry temperature well over an inflection point beyond which the marginal damages associated with warming start decreasing."

References

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