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The U.S. Government's Social Cost of Carbon Estimates after their First Year: Pathways for Improvement

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Abstract In 2010, the U.S. government adopted its first consistent estimates of the social cost of carbon (SCC) for government-wide use in regulatory cost-benefit analysis. Here, we examine a number of the limitations of the estimates identified in the U.S. government report and elsewhere and review recent advances that could pave the way for improvements. We consider in turn socioeconomic scenarios, treatment of physical climate response, damage estimates, ways of incorporating risk aversion, and consistency between SCC estimates and broader climate policy.

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1 Introduction

1.1 Development of the U.S. Social Cost of Carbon Estimates

The social cost of carbon (SCC) is the marginal external cost of a unit emission of CO₂, denominated in terms of forgone consumption and based upon the damages inflicted by that emission upon global society through additional climate change. The value of the SCC is generally estimated in an integrated assessment modeling (IAM) framework that couples a baseline socioeconomic scenario, a climate-carbon cycle model that transforms emissions into temperature, and a function for transforming temperature change (implicitly or explicitly by way of climate change impacts) into economic damages (Figure 1).

In 2010, the United States government established its first consistent estimates of the SCC for government-wide use in cost-benefit analysis of federal regulations (Interagency Working Group on the Social Cost of Carbon, United States Government, 2010). Its analysis relied upon the climate and damage modules of three reduced-form IAMs – DICE 2007 (Nordhaus, 2008), PAGE 2002 (Hope, 2006) and FUND 3.5 (Anthoff and Tol, 2010; Tol, 1997). Five socio-economic scenarios and three fixed discount rates (5%, 3%, and 2.5%) were specified exogenously. Pooling across models and socio-economic scenarios, the report provided four time series of SCC values, increasing over time and starting in 2010 at \$5, \$21, \$35, and \$65 per ton CO₂ (in 2007 dollars). The first three values correspond to mean estimates at discount rates of 5%, 3%, and 2.5%; the last value is the 95th percentile of pooled estimates at the 3% discount rate.

The report describing the analysis, first published in March 2010 as an appendix to the Technical Support Document for DOE's Energy Conservation Standard (ECS) for Small Electric Motors (U.S. Department of Energy, 2010b), identified a number of limitations with the three IAMs it employed to calculate climate change damages. In particular, it noted that all three models:

- Incompletely treated non-catastrophic damages, for instance omitting ocean acidification and other effects on ecosystem services;
- Incompletely treated potential catastrophic damages, such as the effects of major reorganizations of ocean circulation or massive ice sheet melt;
- Crudely extrapolated damages calibrated at low degrees of warming (around 2.5°C) to high degrees of warming (in some scenarios, 10°C or more);
- Failed to incorporate inter-sectoral interactions (such as the effects of water resources on agriculture) and inter-regional interactions (such as the effects of human migration between regions);
- Did not account for the imperfect substitutability of environmental amenities, assuming instead that it is possible to fully replace damaged natural systems with market goods; and
- Incompletely and opaquely treated adaptation to climate changes.

As the report noted, the analysis also did not take into account risk aversion, a factor which plays a large role in broader climate policies, which are often framed as insurance against the risks of climate change. Indeed, by opting for fixed discount rates instead of employing the

42 Ramsey discounting built into all three models, the analysis eliminated the limited mechanism
43 available in the models for incorporating risk aversion.

44 Subsequent critiques noted that the socio-economic scenarios employed in the report
45 significantly undersample the range of plausible futures (O'Neill, 2010) and that the strong
46 simplifications employed in the IAMs' climate models can significantly affect final results
47 (Marten, 2011; van Vuuren et al., 2011; Warren et al., 2010).

48 The report expressed "all due humility" about the limitations of the analysis and pledged that
49 the United States government would periodically review and reconsider SCC estimates.

50 To lay the groundwork for re-examination of the assumptions used in the SCC analysis, the U.S.
51 Department of Energy (DOE) and the U.S. Environmental Protection Agency (EPA) convened a
52 pair of workshops in Nov. 2010 and Jan. 2011. These workshops focused respectively on the
53 broader methodological challenges of calculating climate change damages
54 (<http://go.usa.gov/426>) and on specific sectoral estimates of climate change impacts and
55 damages that might inform the construction and calibration of damage functions
56 (<http://go.usa.gov/42F>). Papers from these workshops will be published in a forthcoming special
57 issue of *Climatic Change*. In addition, significant independent advances have occurred in the
58 relevant research since the U.S. government analysis began.

59 After first examining the application of the U.S. SCC estimates in recent practice, this paper
60 reviews these advances. We start by considering the three principle components of the SCC
61 calculation: socio-economic scenario development, physical climate modeling, and damages
62 estimation. We then examine the challenge of taking risk aversion into account when integrating
63 across possible future states of the world and the consistency between SCC estimates and
64 broader climate policy. We conclude with a discussion of possible steps for refining SCC
65 estimates and directions for future research.

66 **1.2 Initial Applications of the U.S. SCC estimates**

67 Since the release of the U.S. government SCC analysis, its estimates have been employed in
68 several rulemakings by the U.S. Department of Energy (DOE), Environmental Protection
69 Agency (EPA), and Department of Transportation (DOT) (Table 1).

70 To illustrate how SCC estimates are applied in practice, we consider their use in DOE Energy
71 Conservation Standards (ECS). Although the SCC was employed in two final ECS rules and
72 one proposed rule in 2010, it was only one of many inputs used in determining the rules'
73 stringency. The Environmental Policy and Conservation Act (EPCA) requires that standards be
74 technologically feasible and economically justified, and have positive average lifecycle cost
75 savings, and it prescribes eight criteria for consideration in determining economic justification.
76 As part of their associated economic analyses, ECS rules currently assess consumer net present
77 value (NPV) based on initial costs and energy savings, the global monetized benefits of CO₂,
78 NO_x, and mercury emissions reductions, and the sum of these values.¹

79 The monetized benefits of CO₂ are generally a second-order contributor to the NPV of
80 residential and commercial energy efficiency standards, as can be seen by considering the

¹ NO_x and mercury reduction benefits are monetized based on literature surveys. Per ton values are around \$2 thousand and \$17 million per metric ton, respectively, while the total value of NO_x and mercury emission reductions for ECS rule is typically (e.g., U.S. Department of Energy, 2010b) at least an order of magnitude less than CO₂ reduction benefits.

81 average cost and carbon intensity of electricity in the United States. The average retail price of
 82 electricity in 2009 was about 11 cents/kWh, while average CO₂ intensity was about 0.6 kg/kWh
 83 (U.S. Energy Information Administration, 2011a, 2011b). At \$21/ton CO₂, this translates to a
 84 social cost associated with the climate impacts of average US electric generation of about 1.3
 85 cents/kWh conserved. Thus the current central SCC estimates should increase the monetized
 86 benefits of energy efficiency rules for electricity-using products by about ten percent. Higher
 87 SCC estimates, or the incorporation of additional benefits of reduced fossil fuel use (e.g.,
 88 Epstein et al., 2011), would have a larger effect.

89 For each standards analysis, DOE defines several Trial Standard Levels (TSLs) with
 90 increasingly stringent energy efficiency requirements, undertakes a technical and economic
 91 analysis of each level, then selects a TSL based on its analysis. Typically, five to eight different
 92 levels are considered, with the TSL 1 being the least efficient level and the highest TSL being
 93 the maximum technologically feasible. (Masur & Posner (2011) note that the decision to
 94 consider only particular discrete TSLs, rather than explore a broader parameter space, limits the
 95 role of the SCC in stringency setting.) Table 2 compares the selected TSL for final and proposed
 96 rules issued after February 2010 to those TSLs yielding peak NPV at 7% and 3% discount rates,
 97 excluding and including externalities. Where ranges are shown, they reflect the range in SCC
 98 values.

99 Most notable are the proposed refrigerator rules and the residential water heater rule. For
 100 refrigerators, the inclusion of the SCC supports the selection of a more stringent TSL. Without
 101 accounting for externalities, the peak NPV for standard refrigerator-freezers occurs at TSL 1;
 102 with externalities (specifically, the monetized costs of CO₂, NO_x, and mercury emissions), peak
 103 NPV occurs at TSLs 1-3, depending on the SCC value used. DOE selected TSL 3, which was
 104 also the choice of a consensus agreement between industry and advocates.

105 By contrast, the water heater rule illustrates a case in which SCC considerations were
 106 marginalized by other factors. The final rule was set at TSL 5, consistent with the peak NPV in
 107 the absence of externalities at a 7% discount rate. With externalities included and employing the
 108 central SCC estimates, peak NPV occurs at TSL 7 when considering consumer benefits at a 7%
 109 discount rate and at TSL 8 when considering consumer benefits and externalities at a 3%
 110 discount rate. DOE's selection of a less stringent TSL was dominated by distributional
 111 concerns, as can be seen from the text of the rule, which also serves to exemplify the reasoning
 112 underlying ECS rulemakings (U.S. Department of Energy, 2010a):

113 The Secretary has concluded that at TSL 7, the benefits of energy savings, positive consumer NPV (at 3-
 114 percent discount rate), generating capacity reductions, and emission reductions would be outweighed by the
 115 negative economic impacts on those consumers that would have to make structural changes to
 116 accommodate the larger footprint of the heat pump water heaters, the economic burden on a significant
 117 fraction of consumers due to the large increases in total installed costs associated with heat pump water
 118 heaters, the disproportionate impacts to consumers in multi-family housing and others with comparatively
 119 low usage rates, the large capital conversion costs that could result in a large reduction in [Industry Net
 120 Present Value, or] INPV for the manufacturers, and the uncertainties associated with the heat pump water
 121 heater market....

122 The Secretary has concluded that at TSL 5, the benefits of energy savings, positive consumer NPV,
 123 generating capacity reductions, economic savings for most consumers, and emission reductions (both in
 124 physical quantities and the monetized value of those emissions) outweigh the large capital conversion costs
 125 that could result in a large reduction in INPV for the manufacturers and the negative impacts on some
 126 consumer subgroups. Further, global benefits from carbon dioxide reductions (at a central value of \$21.4
 127 per ton for emissions in 2010) would have a present value of \$2.7 billion. These benefits from carbon

128 dioxide emission reductions, when considered in conjunction with the consumer savings NPV and other
129 factors described above, support DOE's conclusion that TSL 5 is economically justified.

130 As this discussion illustrates, the SCC estimates are one of many considerations that inform the
131 regulatory process. In some cases, they have supported the selection of more stringent rules,
132 while in other cases, other factors have proven determinative.

133 **2 Socio-Economic Scenarios**

134 **2.1 Challenges of long-term projections**

135 The first step in calculating the SCC requires identifying baseline scenarios for key socio-
136 economic parameters, such as GDP and emissions. Reference scenarios for mitigation typically
137 extend no further than 2100. Examples include those in the Intergovernmental Panel on Climate
138 Change's Special Report on Emissions Scenarios (SRES) (Intergovernmental Panel on Climate
139 Change, 2000), the under-development Shared Socio-economic Pathways (SSPs) (Kriegler et
140 al., 2010), and the reference scenarios employed by most of the models that participate in
141 Energy Modeling Forum (EMF) model comparison exercises (Clarke, 2009).

142 SCC calculations, however, need multi-century baselines. While projections past 2100 are
143 extremely challenging and at best illustrative, they have a significant effect on the NPV of
144 climate change damages. In DICE 2007's base run, for example, about half of the NPV of total
145 damages at a 3% discount rate comes from damages occurring after 2100 and about 15% comes
146 from damages after 2200. At a 2.5% discount rate, about two-thirds of NPV damages come
147 from impacts after 2100 and one-quarter from impacts after 2200.

148 The U.S. government analysis employed multi-century extensions of reference scenarios from
149 four of the ten process-based IAMs that participated in the EMF-22 exercise (MiniCAM,
150 MESSAGE, MERGE, IMAGE) (Clarke, 2009). The EMF-participating models include more
151 detailed representations of the climate system, the energy system and, in some cases, other
152 physical and economic systems than do reduced-form IAMs. The four reference scenarios were
153 chosen to span the range of reference CO₂ emissions in all ten participating models. (A fifth
154 scenario employed in the U.S. government analysis averaged 550 ppm CO_{2e} stabilization
155 scenarios from the same four models.)

156 As noted by O'Neill (2010), however, the EMF-22 reference scenarios significantly
157 undersample plausible future socio-economic scenarios – an illustration of the general principle
158 that ensembles of complex models tend to oversample the peak and undersample the tails of
159 probability distributions (Roe, 2010). For instance, MiniCAM, MESSAGE, MERGE, and
160 IMAGE all employ moderate population growth scenarios, with population in 2100 in the range
161 of 8.5-10.5 billion. By contrast, the U.N. Low, Medium, and High population scenarios reach
162 6.2, 10.1 and 15.8 billion in 2100, respectively (United Nations Department of Economics and
163 Social Affairs, 2011). The U.S. government analysis extended the four IAM-based population
164 scenarios to 2300 by assuming that population growth rate declined linearly to zero by 2200,
165 yielding a population range of about 8-12 billion by 2300. By contrast, U.N. projections for
166 2300, based on a range of plausible assumption about fertility rates, vary from 2 to 36 billion
167 (United Nations Department of Economics and Social Affairs, 2004). O'Neill et al. (2010)
168 observe that varying assumptions about population can have sizeable impacts on global CO₂

169 emissions; the UN range of population projections for 2100 can lead to a $\sim\pm 50\%$ range in CO₂
170 emissions in the same year.

171 O'Neill (2010) raises similar concerns about the range of GDP scenarios used in the U.S.
172 government analysis, which were based on the EMF scenarios through 2100 and extrapolated a
173 linear decline in the GDP/capita growth rate thereafter. He suggested the need for studies to
174 assess the sensitivity of the SCC to the range in scenarios; assuming it proves significant, he
175 recommended a more thorough process for generating the multi-century socio-economic
176 scenarios needed by the SCC calculations. One approach might be to develop a consistent
177 methodology for extending SSPs to 2300. With the discounting methodology used in the U.S.
178 government SCC analysis, higher future GDP values will increase SCC estimates; with Ramsey
179 discounting, in which the utility of a marginal dollar declines with wealth, the direction of the
180 impact is unclear.

181 Translating GDP into emissions requires technological assumptions. Here, the U.S. government
182 analysis employed carbon intensities from the EMF models through 2100, and then extended a
183 constant CO₂ intensity decline rate thereafter. The reduced-form IAMs employ a similar
184 approach in their native versions. O'Neill notes that the range of emissions in the scenarios
185 employed by the U.S. government analysis is moderately wider than the range in the extended
186 Representative Concentration Profiles that will be used for the IPCC's Fifth Assessment Report.

187 **2.2 Overshoot and panic?**

188 The reference scenarios employed in the U.S. government analysis may not reflect the most
189 likely human responses to climate change. In keeping with the standard definition of a reference
190 scenario, they were calculated for worlds that neither experience climate change impacts nor
191 implement any mitigation policy. Keeping policy (or the lack thereof) constant, these scenarios
192 were then used to calculate the damages to the global economy resulting from climate change –
193 assuming that human civilization chose to suffer and to adapt to climate change, but never to
194 mitigate. In reality, even a highly myopic society would likely undertake some mitigation
195 efforts once the effects of climate change became sufficiently apparent and severe. More
196 plausible alternative reference scenarios – ones reflecting the probable human response in the
197 absence of significant near-term mitigation – might reflect an “overshoot and panic” response
198 (Figure 2).

199 “Overshoot and panic” scenarios can be characterized by the degree of warming sufficient to
200 trigger a ‘panic’ reaction, the level of warming at which society will aim once it panics, and the
201 timescale over which it seeks to achieve this level of warming. For a probabilistic SCC
202 calculation, all three of these parameters could be treated as random variables. Alternatively,
203 assuming that society overcomes barriers to efficient behavior once it starts to panic, the latter
204 two could be calculated through a cost-benefit optimization. In addition to being potentially
205 more realistic, these scenarios have another key benefit: assuming that ‘panic’ onsets at
206 moderate levels of warming (e.g., 2-4°C), they reduce the contribution to the SCC of highly
207 uncertain economic damages triggered by extreme warming.

208 **3 Physical climate and carbon cycle models in IAMs**

209 Carbon cycle and physical climate models translate greenhouse gas emissions associated with a
210 socio-economic scenario into projections of greenhouse gas concentrations, radiative forcing,
211 and temperature.

212 Carbon cycle models project the accumulation of carbon dioxide in the atmosphere and its
213 removal into sinks such as the terrestrial biosphere, the surface ocean, the deep ocean, and
214 ultimately sediments. Though about 30-70% of atmospheric carbon dioxide is removed on a
215 timescale of less than a century, a significant chunk (about 10-20%) remains for ten or more
216 millennia (Archer et al., 2009). The long-term dynamics of other climate forcers, such as
217 methane, are generally simpler than those of carbon dioxide; the removal of such forcers from
218 the atmosphere can often be reasonably well approximated by an exponential decay.

219 The accumulation of greenhouse gases and other climate forcers gives rise to a global energy
220 imbalance that is gradually relieved as the planet adjusts to a new equilibrium temperature. The
221 degree of imbalance is measured by radiative forcing, and the level of equilibrium warming
222 associated with a given forcing is summarized by a parameter known as equilibrium climate
223 sensitivity. In the absence of feedback effects, the equilibrium temperature response to a
224 doubling of CO₂ concentrations (a radiative forcing of 3.7 W/m²) would be about 1.2°C. Fast-
225 feedback climate sensitivity takes into account amplifying feedbacks that respond to forcing on
226 roughly sub-annual to annual timescales, such as changes in atmospheric water vapor, clouds,
227 and snow and sea ice (Randall et al., 2007). The IPCC's Fourth Assessment Report estimated a
228 67% probability that the fast-feedback climate sensitivity was between 2°C and 4.5°C per CO₂
229 doubling, with a most likely value of about 3°C (Hegerl et al., 2007). This assessment was used
230 to help calibrate the probability distribution for climate sensitivity used by the U.S. government
231 analysis.

232 Since the ocean acts as a heat sink, the Earth does not instantaneously adjust to the equilibrium
233 temperature associated with a forcing. The transient climate response – the warming realized
234 after 70 years of a gradual, 1%/year increase in CO₂ concentration (sufficient to cause a
235 doubling of CO₂) – is one way of assessing this delay. An analysis of twentieth-century
236 warming using three different climate models leads to an estimated median value for transient
237 climate response of 2.1°C, with a 90% range of 1.5°C to 2.8°C (Hegerl et al., 2007; Stott et al.,
238 2006).

239 As reviewed by van Vuuren et al. (2011), DICE, FUND and PAGE all employ highly simplified
240 representations of these natural systems. For temperature calculations, DICE uses a two-box
241 model of the surface and the deep ocean; for carbon cycle calculations, it employs a three-box
242 model of the atmosphere, surface ocean/terrestrial biosphere, and deep ocean. PAGE and FUND
243 use functional representations of the decay of greenhouse gas concentrations in the atmosphere
244 and the transient adjustment of temperature toward equilibrium.

245 By contrast, more detailed, process-based IAMs employ a range of more sophisticated climate
246 and carbon cycle models. Several rely upon MAGICC, an upwelling-diffusion energy balance
247 model with a six-box carbon cycle (Meinshausen et al., 2011). IGSM employs an Earth System
248 Model of Intermediate Complexity (EMIC) including representations of atmospheric dynamics
249 and chemistry, sea ice, the terrestrial biosphere, and either a two-dimensional or three-
250 dimensional ocean model (Sokolov et al., 2005). At the high-end of IAM climate model
251 complexity, the Integrated Earth System Model (IESM) project is working to couple the GCAM
252 IAM, which traditionally has employed MAGICC, to the NCAR Community Earth System
253 Model, a fully-coupled global climate model (Clarke, 2010).

254 Compared to DICE and PAGE, the climate and carbon cycle models in FUND exhibit reduced
255 sensitivity of climate to changes in greenhouse gas emissions (Warren et al., 2010). This

256 reduced sensitivity should lower SCC estimates. Both FUND and PAGE respond less quickly
 257 to changes in forcing than do the higher-complexity models that contributed to assessments and
 258 group modeling exercises such as the IPCC's Fourth Assessment Report and the Coupled
 259 Carbon Cycle Model Intercomparison Project (C4MIP). This slow response will postpone
 260 climate impacts and consequently also reduce SCC estimates (van Vuuren et al., 2011).

261 PAGE incorporates strong climate-carbon cycle feedbacks and therefore exhibits greater post-
 262 2100 warming than DICE and FUND (Warren et al., 2010). Indeed, these feedbacks are
 263 significantly stronger than in higher-complexity models (van Vuuren et al., 2011), and so will
 264 increase SCC estimates by PAGE at low discount rates. By contrast, the carbon cycle model in
 265 DICE removes CO₂ from the atmosphere more rapidly than in higher-complexity models (van
 266 Vuuren et al., 2011), which will lead to lower SCC estimates.

267 Marten (2011) examines directly the effects of such simplifications on the social cost of carbon.
 268 Using a variant of DICE with the DICE climate model replaced by a three-box upwelling
 269 diffusion energy balance model calibrated against MAGICC 5.3, he finds SCC estimates at a
 270 3% discount rate that are about 25% higher than those from FUND and 40-50% less than those
 271 from DICE and PAGE.

272 4 Damages

273 4.1 Damage function formulation and calibration

274 In reduced-form IAMs, damage functions translate changes in physical climate parameters – at
 275 least temperature, and sometimes other parameters such as CO₂ concentrations – into changes in
 276 global production or consumption. The US government analysis employed the default damage
 277 functions in DICE, FUND, and PAGE.

278 In DICE and PAGE, damage functions take the form of a modified polynomial; DICE 2007's
 279 default damage function, for example, is given by

$$\begin{aligned}
 280 \quad & D(T)/Y = 1 - 1/(1 + \eta T^\beta) \\
 281 \quad & \eta = \eta_{\text{non-catastrophic}} + \eta_{\text{catastrophic}} = 0.28\% \quad (1) \\
 282 \quad & \eta_{\text{non-catastrophic}} = 0.10\%, \eta_{\text{catastrophic}} = 0.18\%, \beta = 2
 \end{aligned}$$

283 where $D(T)/Y$ represents the fractional reduction in production as a function of warming T , $\eta_{\text{non-}}$
 284 catastrophic scales damages due to gradual and more certain impacts, and $\eta_{\text{catastrophic}}$ scales expected
 285 damages due to high-impact, uncertain-probability events. Note that, for sufficiently low values
 286 of ηT^β , $D(T)/Y \approx \eta T^\beta$; the default DICE damage function is thus an approximately quadratic
 287 function of temperature at low levels of warming.

288 Total expected damages in DICE 2007 are thus about 1% of GDP at 2°C of warming, 4% of
 289 global GDP at 4°C of warming, and 22% of global GDP at 10°C of warming. The DICE
 290 damage function is calibrated at about 2.5°C warming based on a literature review covering
 291 damage models for the agriculture, coastal regions, forestry, energy consumption, health, and
 292 leisure, as well as upon the modelers' estimates of the value of human settlements and
 293 ecosystems (Nordhaus, 2007; Nordhaus and Boyer, 2000). Potential catastrophic impacts are
 294 calibrated based on an adjusted mid-1990s expert elicitation study (Nordhaus, 1994). (DICE
 295 2010, which is an unpublished beta version, explicitly estimates sea level rise and adds terms to
 296 the denominator of equation (1) that are linear and quadratic in sea level rise.)

297 FUND more explicitly models sectoral impacts, with FUND 3.5 containing damage functions
298 for agriculture, forestry, water resources, energy consumption, sea level rise, ecosystems,
299 human health, and extreme weather. It does not attempt to include possible high-impact,
300 uncertain-probability consequences of climate change (Anthoff and Tol, 2010). The version
301 used in the U.S. government analysis projected that climate change would initially have positive
302 benefits – primarily due to reduced cold-stress – with benefits decreasing starting at about 2°C
303 of warming; this version projected net damages at >3°C of warming that leveled off at <10% of
304 global GDP by about 8°C of warming.

305 The mismatch in the sectoral breakdown of damages between DICE and FUND (Figure 3)
306 highlights the need for considerable refinement of sectoral damage estimates. In this context, it
307 is worth noting that calibration of IAM damage functions against sectoral models is an
308 inherently limited approach that would be strengthened by comparison to retrospective analyses
309 of climate change impacts. For example, Lobell et al. (2011), for example, estimate that the
310 effects of temperature change, precipitation change, and CO₂ fertilization from 1980-2008 led to
311 a global average increase in the price of maize, rice, wheat and soybeans of about 6%.

312 Moreover, the fat-tail uncertainty in climate sensitivity requires damage functions that yield
313 meaningful results at high levels of warming – in some cases, >10°C. Such levels are well
314 outside the calibration range of DICE and FUND, and as a consequence these functions yield
315 questionable results when so extrapolated. The DICE damage function, for instance, indicates
316 losses of about 33% of GDP at 11°C of warming – a large amount, but one that prima facie
317 seems inconsistent with the suggestion from recent climate modeling (Sherwood and Huber,
318 2010) that such warming would render uninhabitable the current homelands of most humans.

319 IAM damage functions would benefit from the addition of calibration points at temperature
320 beyond 3°C. In particular, integrative studies bringing together natural and social scientists to
321 examine suites of climate change impacts and plausible associated economic damages in a 4°C
322 or 8°C warmer world would help identify appropriate functional forms. In the absence of such
323 studies, there are few reasons to consider the default damage functions but exclude from
324 consideration the suite of alternative functional forms for DICE-like models that have been
325 proposed in the literature (Ackerman et al., 2010; Azar and Lindgren, 2003; e.g., Lempert et al.,
326 2000; Sterner and Persson, 2008; Weitzman, 2010). Golub et al. (this issue) examine the impact
327 of these alternative formulations on the SCC.

328 **4.2 High-consequence “catastrophic” impacts**

329 As noted by the U.S. government report and due in part to the near absence of the underlying
330 economic literature, the damage functions of IAMs poorly handle high-consequence
331 “catastrophic” climate change impacts. Lenton et al. (2008) identify a suite of possible Earth
332 system “tipping elements”– elements of the Earth system that could undergo radical changes as
333 climatic thresholds are crossed. Among potential tipping element behaviors are: Arctic sea ice
334 loss, Greenland ice sheet melt and West Antarctic ice sheet collapse, slowdown or shutdown of
335 the Atlantic Meridional Overturning Circulation, changes in the amplitude or frequency of El
336 Niño-Southern Oscillation (ENSO), and dieback of the Amazon Rainforest.

337 Krieglger et al. (2009) conducted an expert elicitation study of the probability of crossing certain
338 tipping points under different climate change scenarios. They find a lower-bound probability of
339 16% of crossing at least one tipping point in a medium warming scenario (2-4°C above 2000

340 levels) and a lower bound probability of 56% of crossing at least one tipping point in a high
341 warming scenario (>4°C above 2000 levels).

342 Estimates of the probability of crossing Earth system tipping points can be informed by the
343 study of the geological record of past warm periods. For example, Earth history can provide
344 information about the susceptibility of ice sheets to melt (e.g., Kopp et al., 2009), potential
345 changes to ENSO (e.g., Fedorov et al., 2006), and carbon cycle feedbacks that might amplify
346 future warming (e.g., Zachos et al., 2008).

347 The three reduced-form IAMs used in the U.S. government analysis handle possible
348 catastrophic impacts in different ways. The DICE 2007 damage function includes expected
349 damages associated with a potential catastrophe causing a permanent loss of 30% of global
350 GDP, with the probability of that catastrophe set based on adjustments to an expert elicitation
351 study conducted in the early 1990s (Nordhaus, 1994; Nordhaus and Boyer, 2000). PAGE 2002
352 assumes that a climatic “discontinuity” causing between 5% and 20% loss of GDP becomes
353 increasingly likely as temperatures increase. FUND does not include potential catastrophic
354 impacts (Figure 4).

355 It is important to note that crossing an Earth system tipping point is not identical to the onset of
356 a catastrophic climate change event. For example, some major changes in the Earth system may
357 take place over periods long enough for society to adapt with fairly limited costs. With a partial
358 and limited exception in the case of sea level rise associated with ice sheet collapse, the
359 literature on the economic consequences of Earth system tipping points is extremely sparse (but
360 see Lenton et al., 2009).

361 **4.3 Inter-sectoral and inter-regional interactions**

362 As the U.S. government report highlighted, another area of weakness in the IAM damage
363 functions involves interactions between sectors and between regions. Warren (2011) notes the
364 potential of process-based IAMs like GCAM (Clarke, 2010) to address such interactions. She
365 notes some intersectoral interactions which have been quantified but not typically included in
366 integrated assessments, including the effects of:

- 367 • Changes in biome type on soil moisture content, evapo-transpiration rate, and thus
368 overall hydrology;
- 369 • Farmland loss owing to sea-level rise and salinization on the agriculture sector;
- 370 • Loss of pollinators, loss of wild crop types, and pest and diseases on agriculture;
- 371 • Changes in coastal ecosystems on coastal regions and biodiversity;
- 372 • Land conversions owing to shifts in agricultural production on terrestrial ecosystems;
- 373 • Keystone species extinction on terrestrial ecosystems;
- 374 • Lost ecosystem services on human health.

375 She also identifies a number of poorly quantified impacts, including the effects of:

- 376 • Changes in nutrient run-off on coastal regions;
- 377 • Agricultural intensification on biodiversity;
- 378 • Loss of calcifying species due to ocean acidification on marine ecosystems;
- 379 • Construction on dams on human health;
- 380 • Saltwater intrusion on human health;
- 381 • Subsidence and dam construction on settlements and infrastructure.

382 Regarding interregional interactions – in particular human migration – Warren suggests that a
383 process-based approach may be infeasible and instead recommends a scenario-based
384 methodology. She notes projections that, in a 4°C warmer world, about 800 million people are
385 expected to experience increased water stress and that 30% of global land area (up from 1%
386 today) is expected to experience drought at any one time.

387 **4.4 Complementary approaches**

388 Cooke (2010) suggests using “outer measures” of climate change damages as a complement to
389 the “inner measures” currently employed. By analogy to mathematical measure theory, an
390 “outer measure” assesses a superset of the true set of damages, while an “inner measure”
391 assesses a subset of damages. (An inner measure of climate damages can be compared to the
392 proverbial man looking for his keys only in the illuminated areas under a streetlight, while an
393 outer measure might encompass the entire area he has traversed since he last saw his keys.) As
394 the outer measure becomes more tightly defined and the inner measure more comprehensive,
395 they should converge. The damage estimates currently employed are all inner measures, built up
396 from estimates of individual sectoral impacts and, as noted previously, often missing potential
397 key effects. Cooke suggests that the quantitative literature on the relationship between climate
398 and development could help guide the construction of outer (or at least alternative and
399 independent) measures. For example, analyzing cross-section municipal data from twelve
400 countries in the Americas and 2 to 5 decades of national-level panel data from 136 countries,
401 Dell et al. (2009) estimate that, net of adaptation, warming acts to decelerate growth by about
402 0.5%/year per degree C. If GDP grows at 3%/year under the reference scenario, then by
403 Cooke’s reasoning, one outer measure of expected GDP loss after 50 years of 3°C warming
404 would be about 50% of GDP (i.e., GDP after 50 years would have grown by 110% instead of
405 340%).

406 **5 Risk aversion**

407 The U.S. government SCC estimates are based on Monte Carlo samples from the probability
408 distribution for climate sensitivity, as well as for a suite of other random variables employed in
409 the standard version of PAGE and the stochastic version of FUND. These Monte Carlo samples
410 yield probability distributions for the social cost of carbon. One key question is how to
411 summarize these distributions in a single value. For three of its four SCC estimates, including
412 the central estimate, the report took the mean of the distribution – the value that would be used
413 by a risk-neutral utility maximizer – while the fourth value was sampled from the 95th percentile
414 of the distribution with a 3% discount rate.

415 Yet climate policy is generally viewed not simply as a way of maximizing risk-neutral expected
416 utility but as a way of managing risk. The United Nations Framework Convention of Climate
417 Change (UNFCCC), for example, seeks to “prevent dangerous anthropogenic interference with
418 the climate system” (United Nations, 1992). This framing suggests not risk neutrality, but risk
419 aversion, and indicates the need for summary values that give extra weight to low-probability
420 but high-consequence states of the world (e.g., Keller et al., 2005; Oppenheimer and Petsonk,
421 2005).

422 Kousky et al. (this issue) review approaches for incorporating risk aversion into the social cost
423 of carbon, which can be viewed as falling into two basic categories: those that operate through
424 discounting and those that do not. We highlight some key points here.

425 5.1 Risk aversion in Ramsey discounting

426 The conventional Ramsey (1928) discounting framework, as employed in the standard versions
427 of DICE, FUND, and PAGE, assumes an isoelastic utility function, with the time-discounted
428 marginal utility u of consumption c and time t given by:

$$429 \quad u(c,t) = c^{-\eta}/(1 + \rho)^t \quad (2)$$

430 where η is the elasticity. Assuming a consumption growth rate of g , such that $c(t) = c_0(1 + g)^t$,
431 and a pure rate of time preference of ρ , the deterministic discount rate r can be calculated by
432 equating the utility of one unit of consumption at time t with the utility of $(1 + r)$ units of
433 consumption at time $(t + 1)$. It is given by

$$434 \quad c_0^{-\eta} = (1 + r) [c_0 (1 + g)]^{-\eta}/(1 + \rho)$$

$$435 \quad (1+r) = (1 + \rho)(1 + g)^{\eta}, \quad (3)$$

436 which can be approximated by the well-known expression

$$437 \quad r \approx \rho + g\eta. \quad (4)$$

438 By definition, η is the coefficient of relative risk aversion and a measure of both inter-temporal
439 and intra-temporal inequality aversion. Social welfare is calculated in this framework by
440 summing time-discounted utility across individuals and time periods and averaging across states
441 of the world. If $\eta > 0$, low-consumption states of the world, time periods, and individuals
442 contribute more per unit consumption to social welfare than do their high-consumption
443 counterparts (equation 2). Equivalently, because r is correlated with the consumption growth
444 rate (equation 4), states of the world that experience slow or negative growth are discounted less
445 heavily than high-growth states.

446 The inclusion of moderate levels of risk aversion can therefore have a large impact on SCC
447 values. For example, Anthoff et al. (2009) find in FUND that incorporating risk aversion
448 increases SCC estimates by about \$20/ton CO₂ (using $\rho = 1.1\%$ and $\eta = 1.5$, parameters that
449 would yield a deterministic discount rate of about 5% per annum).

450 The U.S. government analysis does not employ Ramsey discounting. Instead, it employed flat
451 discount rates of 2.5%, 3.0% and 5.0% per annum. Effectively, it set η to zero, removing the
452 only form of risk aversion incorporated into the standard versions of the reduced-form IAMs.
453 By comparison, η is frequently set to 1.0, as in the Stern Review (Stern, 2007). DICE 2010
454 defaults to 1.5, while earlier versions default to 2.0.

455 Dietz (2010) discusses a general problem with isoelastic utility functions: namely, that marginal
456 utility tends to infinity as consumption tends to zero. As a consequence, as observed by
457 Weitzman (2009), cost-benefit analysis with these utility functions fails in situations with
458 extremely high-impact, low-probability ‘fat tails.’ One approach to dealing with this problem,
459 followed by Weitzman and by Dietz, is to bound consumption by assuming that per capita
460 consumption cannot fall below something analogous to the value of a statistical life. Employing
461 fat-tailed distributions for damage function exponents (a log-normal distribution with a mean of
462 1.9 and 90% range of 1.1 to 3.1) and climate sensitivity in a DICE-like framework, Dietz finds
463 that, with damages bounded at 99% of consumption, $\rho = 1.5\%$ and $\eta = 3$, the mean SCC is
464 \$346/ton CO₂, with a 90% confidence range of \$5 to \$1359/ton. (Note that, at a growth rate of

465 2-3%, these parameters would imply a total discount rate of about 7%-11% -- yielding a very
466 small SCC in a deterministic framework.)

467 **5.2 Risk aversion in discounting beyond the Ramsey framework**

468 As noted previously, another key limitation of the Ramsey discounting approach is that it does
469 not distinguish between risk aversion, aversion to inter-temporal inequality, and aversion to
470 intra-temporal inequality. Assuming future generations are wealthier, high risk aversion (which
471 will increase the desire to abate greenhouse gas emissions) will thus also be correlated with a
472 high inter-temporal discount rate (which will reduce the desire to abate emissions). However,
473 results from the Climate Ethics Survey (Atkinson et al., 2009) indicate that attitudes toward risk
474 aversion, inter-generational, and intra-generational equity are only weakly correlated. This
475 survey of over 3000 people found a median value of η in the context of risk aversion in the
476 range of 3-5, a median value of η in the context of intra-temporal equality in the range of 2-3
477 (but with the modal peak at >7.5 and a secondary peak at <1.0). A median value of η in the
478 context of inter-temporal equality of about 8.8 suggests a strong aversion to downward sloping
479 consumption paths.

480 Traeger (2009) reviews some relevant approaches for discounting under uncertainty and for
481 separating out the distinct roles of η . As one example, Crost and Traeger (2010) present a
482 recursive dynamic programming model based upon stochastic growth in a simplified version of
483 DICE. They find that treating uncertainty over climate sensitivity and damages in such a
484 framework (with $\eta = 2$ in a risk aversion context and 0.67 in an intertemporal context, based on
485 Vissing-Jørgensen and Attanasio, 2003) increases SCC estimates off an optimal emissions
486 trajectory by about \$15-\$30/ton CO₂ compared to using the discounting parameters in DICE
487 2007 ($\eta = 2$ in all contexts).

488 Kaplow et al. (2010) note that the positive parameters used to describe the preferences of
489 individuals, which are descriptive and can be inferred from observed market behavior or from
490 surveys, are not necessarily identical to the normative social preferences appropriate for
491 evaluating policies that impact individuals, including some (such as those belonging to future
492 generations) who are not market actors. The former appear in individuals' utility functions,
493 while the latter appear in the social welfare function. They suggest separating out these two
494 functions of η and ρ in IAMs.

495 **5.3 Non-discounting approaches to account for risk aversion**

496 While one method for incorporating risk aversion is through discounting, an alternative
497 approach is to employ decision criteria other than expected utility maximization. McInerney et
498 al. (in rev.) contrast expected utility maximization with two alternative criteria:

- 499 (1) 'limited degree of confidence' (LDC), which maximizes a weighted average of
500 expected utility and a measure of extreme possible outcomes, and
- 501 (2) 'safety first,' which maximizes expected utility subject to a constraint on the probability
502 of high-end impacts.

503 Both these alternative criteria can inform climate policy. The marginals of the associated
504 objective functions can also generate values suitable for consideration as social cost of carbon
505 estimates. For example, as used by McInerney et al., the measure of the worst outcome for the
506 LDC criterion is conditional value at risk, which is the expected value of the worst q -th quantile
507 of the outcome distribution; i.e., the LDC criterion maximizes

$$508 \quad \beta E[W] + (1 - \beta)E[W_q] \quad (5)$$

509 where $(1 - \beta)$ is the weight on high-end outcomes, $E[W]$ is the expectation of social welfare, and
 510 $E[W_q]$ is the expectation of the worst q -th quantile of welfare. In the paradigm of robust
 511 decision-making (Lempert and Collins, 2007), β should reflect the degree of confidence in the
 512 probability distribution for W and thus in expected social welfare. Higher values of β reduce
 513 optimality in return for greater resilience to violated assumptions. This objective function can be
 514 applied in a straightforward fashion to yield a marginal value akin to the SCC:

$$515 \quad \beta E[SCC] + (1 - \beta)E[SCC_q]. \quad (6)$$

516 A similar marginal can be derived from the Lagrangian associated with the ‘safety first’
 517 criterion.

518 **6 Relationship to broader climate policy**

519 **6.1 Consistency in assumptions**

520 A single, expected utility-maximizing decision-maker choosing an economy-wide climate
 521 policy would select a target emissions path that minimizes the combined costs of climate change
 522 impacts and mitigation over time. In the absence of constraints that prevent such a solution, the
 523 marginal abatement costs along the cost-minimizing path will be equal to marginal benefits (the
 524 SCC value associated with the target path, i.e., the shadow price of carbon).

525 The inputs needed by such a decision-maker would resemble those needed for estimation of the
 526 SCC. On the normative side, they include a pure rate of time preference, a measure of risk
 527 aversion, and a measure of inequality aversion. On the positive side, they include a probability
 528 distribution for the stream of economic damages conditional on emissions and, distinct from
 529 SCC calculations, a probability distribution for abatement costs conditional on emissions.

530 Under the Copenhagen Accord, the U.S. set greenhouse gas emission targets of 17% below
 531 2005 by 2020 and 83% below 2005 levels by 2050 (Stern, 2010), while in the Cancun
 532 Agreement, the world’s governments called for “urgent action” to limit warming to 2°C above
 533 pre-Industrial temperatures (United Nations Framework Convention on Climate Change, 2010).
 534 Both of these goals implicitly reflect risk-adjusted cost-benefit optimizations, and taken together
 535 they also imply some distributional preferences. If known or inferred, the assumptions
 536 underlying these optimizations could be used to calculate SCC values, either off the target path
 537 or off a reference path. Conversely, given the assumptions underlying current SCC calculations
 538 and assumptions about abatement costs, it is possible to calculate associated optimal emissions
 539 trajectories.

540 If consistent assumptions underlie both the SCC calculations and broader climate policy,
 541 employing the SCC assumptions to calculate the optimal emissions path should yield back
 542 broader climate targets. However, current U.S. government SCC estimates are risk-neutral,
 543 whereas broader climate policy is based on risk aversion (e.g., the UNFCCC goal of avoiding
 544 “dangerous anthropogenic interference” with the climate system; United Nations, 1992).
 545 Moreover, the implicit damage functions underlying broader climate policy may include
 546 potential impacts that are excluded from the the default damage functions in the models
 547 underlying current SCC calculations. Employing risk neutrality and the default IAM damage

548 functions in an optimization will therefore yield emissions reductions that fall short of accepted
549 targets for broader climate policy.

550 **6.2 Is the baseline SCC the most suitable cost estimate to be using?**

551 Even if the assumptions underlying SCC estimates are chosen to be consistent with broader
552 climate policy, another key question remains: does the SCC calculated off of a baseline
553 emission path provide an appropriate metric with which to evaluate carbon-reducing
554 regulations?

555 The U.S. government's SCC estimates are meant to enable the incorporation of the marginal
556 climatic benefits of CO₂ mitigation into cost-benefit analyses. Even assuming perfect
557 characterization of climate change damages, however, the baseline SCC may not provide a
558 comprehensive measure of these marginal benefits.

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

567 Ignoring temporal dynamics, Figure 5a shows an example of such a situation, with about 600 Gt
568 C cumulative abatement being necessary to avoid crossing a major tipping point. Note that the
569 illustrative marginal abatement and benefits (SCC) curves intersect at three points,
570 corresponding to maxima (points A and C) and minima (point B) of total welfare change
571 (Figure 5b). The baseline SCC (\$30/ton) is nearly indistinguishable from what it would be if the
572 tipping point did not exist, as is the SCC at local welfare maximum A (\$25/ton). But at the
573 global cost maximum, which increases total welfare by \$14 trillion over baseline and \$5 trillion
574 over local maximum A, the SCC and the marginal abatement cost are \$84/ton. The \$5 trillion
575 that society is willing to pay to end up at point C instead of point B makes no impact on the
576 baseline SCC, and applying the baseline SCC in cost-benefit analyses would exclude abatement
577 options society is willing to pursue to reach the global optimum. These considerations suggest
578 that the SCC calculated at the global optimum provides a more robust measure of the marginal
579 climate benefits of abatement than does the baseline SCC.

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

589 Baumol therefore suggests instead circumventing the challenges of optimization by identifying
590 an acceptable level of an externality and imposing a tax sufficient to achieve this level. In the

591 climate change context, his suggestion amounts to setting a temperature, concentration or
592 impact target and then employing a carbon price that achieves this target in a cost-effective
593 manner. Consistent with Baumol's proposal, the government of the United Kingdom shifted in
594 2009 from evaluating regulations using the social cost of carbon to evaluating regulations using
595 "target-consistent" abatement costs (UK Department of Energy and Climate Change, 2009).

596 **7 Next steps**

597 The U.S. government's social cost of carbon estimates have provided its first consistent
598 framework for incorporating the costs of climate change and the benefits of greenhouse gas
599 abatement into the cost-benefit analysis of federal regulations. They supplanted a family of
600 approaches that varied greatly among rules and agencies and most often neglected the costs of
601 climate change altogether. Nonetheless, as the U.S. government report acknowledges, the
602 current estimates are simply a first attempt. Some improvements can be made in light of
603 additional research that has been published since the U.S. government analysis began; other
604 gaps point to the need for further research.

605 The baseline socioeconomic scenarios employed could borrow from and build upon the SSPs
606 under development for AR 5, with a consistent framework applied for translating UN population
607 projections to 2300 into long-term economic projections. Baseline scenarios that take likely
608 "panic" policy responses into account could also be considered.

609 The simple climate models in the reduced-form IAMs employed could be upgraded to emulate
610 the best-available results from more sophisticated climate models.

611 In the short term, the uncertainty associated with calculating climate damages would be better
612 captured by considering a range of damage functions beyond those included by default in DICE,
613 FUND and PAGE, possibly including bounding "outer measures" as well as the more traditional
614 "inner measures." In the longer term, damage models need to be expanded to include missing
615 sectors and to attempt to capture inter-sectoral and inter-regional interactions. Process-based
616 IAMs may play a key role in this expansion.

617 Integrated assessment modelers face considerable challenges when attempting to incorporate
618 high-impact "catastrophic" damages or extrapolating damages to high levels of warming.
619 Progress in these areas requires more detailed economic impact studies focused on the
620 consequences of catastrophic climate change. Both detailed and integrative studies of climate
621 change impacts under high-end warming scenarios could provide additional calibration points
622 for IAMs, the damages in which are largely calibrated only for low levels of warming. And
623 without including risk aversion in some fashion, the SCC estimates will necessarily be
624 inconsistent with broader climate policy, which are based on implicit or explicit judgments of
625 risk.

626 Paradoxically, incorporating some of these changes, including non-convex damage functions,
627 into future estimates could yield SCC values even less consistent with broader climate policy
628 unless other methodological refinements are adopted at the same time. In particular, SCC values
629 calculated off of the baseline path when realistic tipping point impacts are included in the
630 damage function will not account for the benefits associated with avoiding those tipping points.
631 Consistency among climate policy efforts will therefore require further refinements to the

632 methodology – such as calculating the SCC off the optimal path – in order to effectively capture
633 these benefits.

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835 Table 1: Some Applications of the Interagency SCC estimates, March 2010-February 2011

Date	Agency	Rule	Status	URL
March 2010	DOE	ECS for Small Electric Motors	Final Rule	http://go.usa.gov/r80
April 2010	DOE	ECS for Residential Water Heaters	Final Rule	http://go.usa.gov/r8I
May 2010	EPA/ DOT	Light Duty Vehicles and GHG Emissions and CAFE Standards	Final Rule	http://go.usa.gov/r8Q
May 2010	DOT	Automatic Dependent Surveillance—Broadcast (ADS-B) Out Performance Requirements To Support Air Traffic Control Service	Final Rule	http://go.usa.gov/TwD
August 2010	EPA	Federal Implementation Plans To Reduce Interstate Transport of Fine Particulate Matter and Ozone	Proposed Rule	http://go.usa.gov/rMO
Sept. 2010	DOE	ECS for Refrigerators	Proposed Rule	http://go.usa.gov/r8N
Nov. 2010	EPA/ DOT	Heavy Duty Vehicles and GHG Emissions and CAFE Standards	Proposed Rule	http://go.usa.gov/r8Q

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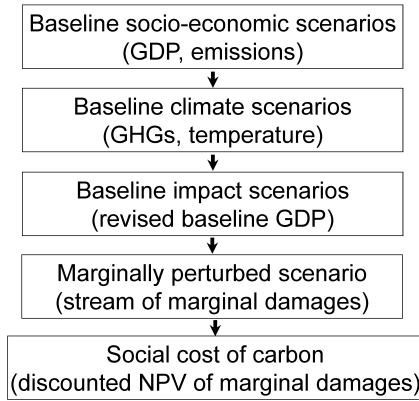
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839 **Table 2:** The influence of the SCC on Trial Standard Level selection for Energy Conservation Standards

Product	Final/ Proposed TSL	Highest TSL	TSL with peak NPV, w/o externalities		TSL with peak NPV, w/ externalities	
			7%	3%	7%	3%
Polyphase Small Electric Motors (SEMs)	4b	7	4b	4b	4b	4b
Capacitor-start SEMs	7	8	7	7	7	7
Water heaters	5	8	5	7	5-8	7-8
Direct heating equipment	2	6	3	3	3	3
Pool heaters	2	6	2	2	2	2
Standard-size refrigerator-freezers	3 (proposed)	5	1	1	1-3	1-3
Standard-size freezers	2 (proposed)	5	1	3	2-3	3
Compact refrigerators	2 (proposed)	5	1	1	1-3	1

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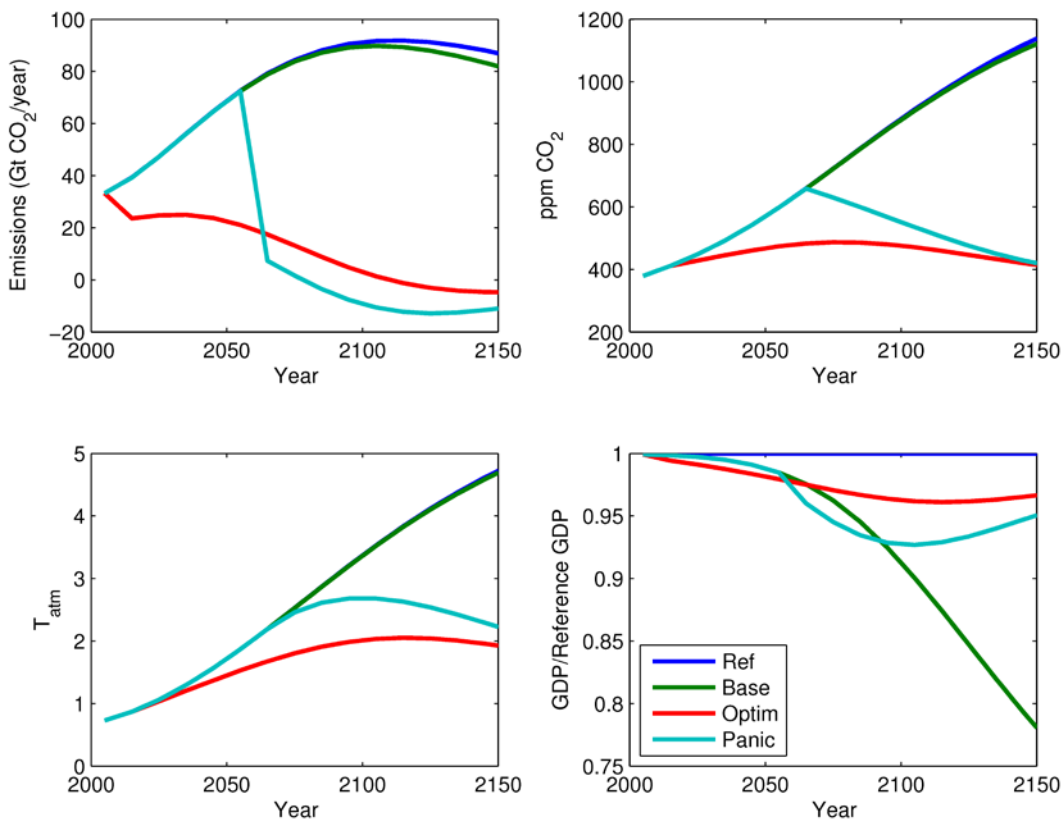


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843 **Figure 1:** Flow process used in calculating social cost of carbon estimates. A reference socio-economic
 844 scenario is used to calculate a reference climate scenario. Economic damages calculated based on this
 845 climate scenario are then used to revise the baseline. Next, the baseline scenario is marginally perturbed
 846 by the additional or removal of a marginal unit of CO₂ emissions. The value of the stream of damages
 847 thus generated is then discounted back to the year of emission.

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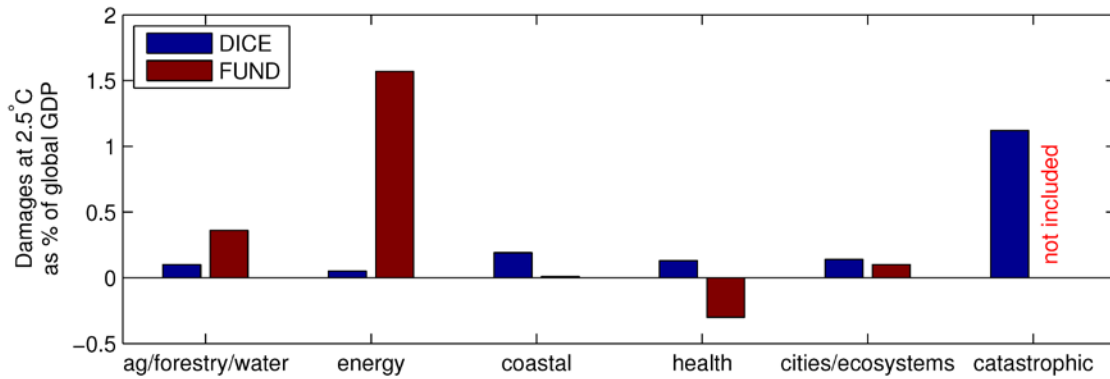
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851 **Figure 2:** (a) CO₂ emissions, (b) CO₂ concentrations, (c) surface temperatures and (d) GDP (net of
 852 climate damages and abatement expenditures) as a fraction of reference scenario GDP for four illustrative
 853 scenarios computed using a DICE-like model. “Ref” (blue) was computed in the absence of climate
 854 damages; “Base” (green) includes damages but retains the absence of mitigation policy in the Ref
 855 scenario; “Optim” (red) is the result of a cost-benefit optimization starting in 2015, while “Panic” follows
 856 Base until warming exceeds 2°C and then follows a cost-benefit optimized pathway.

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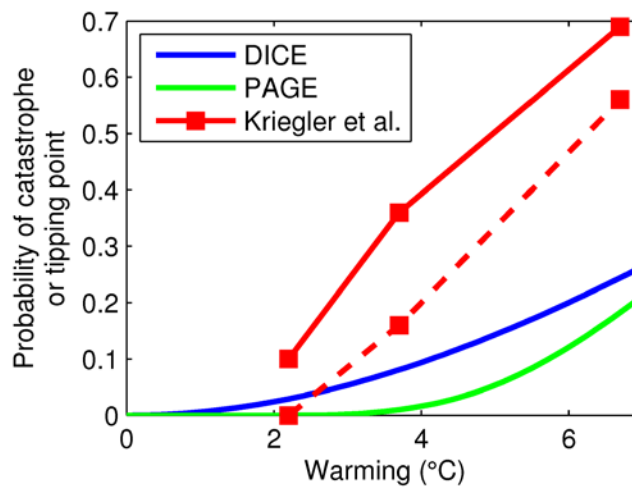


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859 **Figure 3:** Damages by sector in DICE (Nordhaus, 2007) (blue) and a typical FUND2.9 scenario (Warren
 860 et al., 2006) (red) at 2.5°C warming, aggregated into similar sectoral categories. “Ag/forestry/water” bars
 861 correspond to the agriculture sector in DICE and the agriculture, forestry and water resources in FUND.
 862 “Energy” bars correspond to DICE’s “other vulnerable market” sectors and FUND’s energy consumption
 863 sector. “Coastal” bars correspond to DICE’s coastal impacts sector and FUND’s sea level rise damages.
 864 “Health” bars correspond to human health impacts in both models. “Cities/ecosystems” bars correspond
 865 to DICE’s damages to settlements and ecosystems and FUND’s damages to ecosystems. Catastrophic
 866 damages are not included in FUND and are expected values in DICE.

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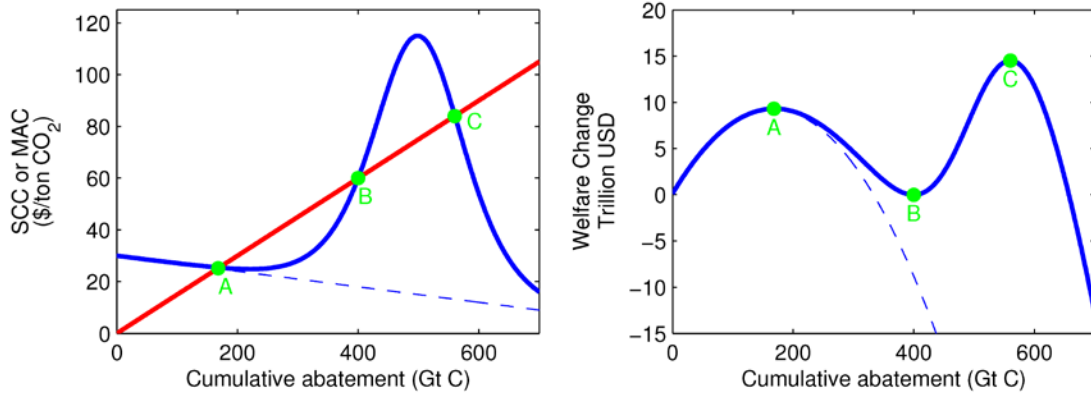
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870 **Figure 4:** Probability of catastrophic damages in DICE 2007 (blue) and PAGE 2002 (green), compared to
 871 lower bounds on the probability of crossing at least one Earth system tipping point according to the expert
 872 elicitation study of Kriegler et al. (2009) (red). The DICE curve is inferred based on the relative
 873 proportions of catastrophic and non-catastrophic damages at 2.5°C and a definition of “catastrophe” as
 874 causing a loss of 30% GDP (Nordhaus, 2007; Nordhaus and Boyer, 2000). In PAGE 2002, catastrophic
 875 damages cause loss of 5-20% of GDP. The two curves from Kriegler et al. are based on two different
 876 ways of pooling expert responses. Note that a biogeophysical tipping point is not identical to an economic
 877 catastrophe, although the examples given by Nordhaus and Boyer (2000) are all associated with tipping
 878 points.

879



880

881 **Figure 5:** (a) Illustrative marginal abatement costs (red) and benefits (blue) curves and (b) total welfare
 882 change for a world in which the majority of climate change damages are associated with a major Earth
 883 system tipping point. The dashed lines show corresponding marginal benefits and total welfare change for
 884 a world without the tipping point. The marginal abatement cost and benefit curves intersect at three
 885 points; point A is a local welfare maximum, point B is a local welfare minimum, and point C is the global
 886 welfare maximum. In the absence of the tipping point, point A would be the global maximum and the
 887 only intersection point. Baseline emissions carry the world well over the tipping point, but the damages
 888 associated with the tipping point have a negligible effect on the SCC at baseline emissions and at local
 889 welfare maximum A.

890

Please note:

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