November 20, 2017

Ms. Kimberly D. Bose, Secretary
Federal Energy Regulatory Commission
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Via email and e-filing

Re: Comments on September 27, 2017 Draft Supplemental Environmental Impact Statement for:

OEP/DG2E/Gas Branch 3
Florida Southeast Connection, LLC
Transcontinental Gas Pipe Line Company, LLC
Sabal Trail Transmission, LLC
(together, Southeast Market Pipelines Project)
Docket Nos. CP14-554-002, CP15-16-003, CP15-17-002

Sierra Club submits these comments concerning the Draft Supplemental Environmental Impact Statement (the "supplemental EIS" or "SEIS") prepared by the Federal Energy Regulatory Commission ("FERC") for the above-captioned projects. This comment is supplemented by separate comments jointly submitted by Sierra Club, Environmental Defense Fund, Institute for Policy Integrity at New York University School of Law, Natural Resources Defense Council, and Union of Concerned Scientists in a separate filing. In addition, this comment supplements and reiterates Sierra Club's March 27, 2017 request for a supplemental EIS.[1]

I. Introduction

In *Sierra Club v. FERC*, the D.C. Circuit held that NEPA analysis of the Southeast Market Pipelines Project must include "a quantitative estimate of the downstream greenhouse emissions that will result from burning the natural gas that the pipelines will transport," "a discussion of the 'significance' of" these emissions, and analysis of "the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions." *Sierra Club v. Fed. Energy Regulatory Comm'n*, 867 F.3d 1357, 1374 (D.C. Cir. 2017). The draft SEIS (hereinafter "SEIS") here fails on all counts. Rather than providing a meaningful basis for choosing between alternatives (including the action and no-action alternatives), the SEIS improperly treats the downstream GHG analysis as an academic exercise to support a pre-determined outcome.

FERC fails to provide even an adequate quantification of indirect emissions, including failing to meaningfully juxtapose the project's indirect emissions with those that would result under any alternative. Even for the emissions estimated in the SEIS, the SEIS provides no discussion whatsoever of these emissions' "significance," including their "cultural, economic, social, or health" impacts. 40 C.F.R. §§ 1502.16(a)-(b), 1508.8. The SEIS simply asserts, without explanation, that the SEIS has not given FERC reason to alter its prior conclusion that "operating the SMP Project would not result in a significant impact on the environment." SEIS at 2.

As such, the SEIS fails to inform FERC's decisionmaking: the SEIS offers no explanation of whether indirect greenhouse gas emissions warrant adoption of additional mitigation measures, an alternative to the proposal, or rejection of the project entirely. *Sierra Club*, 867 F.3d at 1364 ("FERC is also empowered to attach 'reasonable terms and conditions' to the certificate"); *id*. at

[1] Accession No. 20170328-0076.

1374 ("greenhouse-gas emissions are an indirect effect of authorizing this project, which FERC … has legal authority to mitigate."). FERC also must balance the public benefits against the adverse effects, including adverse effects caused by downstream GHG emissions. *Id.* at 1373 ("FERC will balance 'the public benefits against the adverse effects of the project' including adverse environmental effects" (citations omitted)); *id.* (FERC can "deny a pipeline certificate on the ground that the pipeline would be too harmful to the environment").

The protocols developed by the former Interagency Working Group on Social Cost of Carbon remain the best tools for providing this missing analysis. FERC's stated reasons for declining to use this tool here are arbitrary. Even without this tool, however, FERC's implicit determination that a nearly 10% increase in Florida greenhouse gas emissions would be insignificant is arbitrary on its face.

II. The Draft SEIS Understates the Volume of Emissions at Issue

NEPA requires that FERC consider "indirect effects," which are "reasonably foreseeable" effects "caused by" the action, including "growth inducing" effects. 40 C.F.R. 1508.8(b). In *Sierra Club,* the D.C. Circuit Court held that this requires FERC to provide "a quantitative estimate of the downstream greenhouse emissions that will result from burning the natural gas that the pipelines will transport." *Sierra Club,* 867 F.3d at 1374.

Here, the pipelines will deliver 1.1 bcf/d of natural gas. Widely accepted conversion factors[2] indicate that burning 1.1 bcf/d of gas will emit 22.1 million metric tons (MMt/y) per year of carbon dioxide equivalent.[3] The SEIS provides this value, recognizing that it represents "full burn" of the delivered gas. But the SEIS arbitrarily undercuts this disclosure in numerous ways.

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[2] SEIS at 3 n.6; *accord* https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator.
[3] This estimate does not account for non-CO_2 emissions such as fugitive methane. FERC must address these additional emissions in the final SEIS.

First, the SEIS provides a substantially lower estimate of "total" or "gross" downstream emissions without any explanation as to how this estimate can be squared with the "full burn" estimate; it appears that the "total" estimate is indefensible. Second, the SEIS argues that emissions resulting from burning gas delivered by the pipeline will be partially offset by displacement of other fossil fuel consumption, offering a still lower "net" estimate of downstream emissions. However, both the SEIS's general discussion of displacement and the SEIS's particular estimates here are unsupported. Finally, even if the "gross" and "net" estimates were supported by reasonable methodology and data, the SEIS's failure to provide any guidance as to which of the three estimates should be used in assessing the pipeline's impacts—or which FERC used in concluding that these impacts would be insignificant—would render the SEIS inadequate.

A. The Draft SEIS Does Not Support Use of a "Gross" or "Total" Estimate Lower Than the "Full Burn" Estimate

The first and most prominent quantitative estimate of downstream emissions the SEIS provides is wrong, incomplete, or both. Table 1 purports to identify "Total Downstream CO2 Emissions" of 14.5 MMt/y; the SEIS later refers to this value as "gross potential to emit emissions." This estimate does not, however, appear to be a "total" in any meaningful sense of the word: the SEIS explains that "combustion of the total pipeline capacity" would result in more than 50% more emissions (*i.e.*, 22.1 MMt/y) than the purportedly "total" estimate. SEIS at 3-4.

FERC does not explain why the "total" estimate is lower than the "full burn" estimate. The "total" estimate purportedly reflects emissions resulting from use of gas delivered to three specific power plants, assuming these plants run round-the-clock,[4] plus use of the 0.1 bcf/d of

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[4] SEIS at 3 n.4. Other than to state that these estimates assume 8,760 hours per year of operation, the SEIS provides no discussion of how the estimates for each power plant were calculated, nor

capacity that is "uncommitted." SEIS at 3. The SEIS then indicates that the "full burn" estimate reflects the emissions that would result if, rather than "running at full power" 100% of the time, these power plants ran less, such that the gas the power plants otherwise would have used "could be sold to other customers." SEIS at 3. However, FERC provides no explanation as to why burning gas at the power plants rather than other uses would cause combustion emissions to significantly decrease. Burning a given volume of gas will produce roughly the same emissions regardless of whether that combustion occurs in one of these three power plants or elsewhere, as reflected by the very EIA and EPA emission factors the SEIS cites.

Thus, it appears that the "total" or "gross" estimate fails to provide the information the D.C. Circuit instructed FERC to provide: "a quantitative estimate of the downstream greenhouse emissions that will result from burning the natural gas that the pipelines will transport." *Sierra Club*, 867 F.3d at 1374.

An additional source of confusion is that while the SEIS identifies 0.1 bcf/d of pipeline capacity as "uncommitted," the SEIS does not explain where the remaining (and implicitly "committed") 1.0 bcf/d of capacity will go. The only end users identified in the SEIS are the three power plants, which the SEIS states will emit 12.5 MMt/y of CO_2e. SEIS at 3. However, the conversion factor the SEIS relies on indicates that 12.5 MMt/y of CO_2e would be produced by burning only about 0.6 bcf/d of gas, whereas burning 1 bcf/d would be expected to emit closer to

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does the SEIS provide any useful citation. *Cf.* 40 C.F.R. 1502.21. The SEIS states that these estimates are derived from air permits, but the SEIS does not cite these permits, and at the time the SEIS was circulated for public comment, none of the permits were in the docket for this proceeding. Although FERC belatedly filed two permits, the Duke Energy Citrus Plant permit still has not been filed, nor has FERC responded to Sierra Club's Freedom of Information Act request regarding these estimates.

20.1 MMt/y of CO_2e.[5]

The "total" or "gross" emission estimate presented by the SEIS is misleading, incorrect, or both. The SEIS fails to provide a rational explanation as to: how much gas consumption is actually factored into this "total" estimate; whether that number is lower than the total 1.1 bcf/d pipeline capacity (and if so, why); and why the "total" estimate is drastically lower than the "full burn" figure. Insofar as it is the "full burn" estimate that actually indicates the emissions that would result from using the gas capable of being delivered by the pipeline, the final SEIS must clearly indicate to the public and decisionmakers that the "full burn" estimate best illustrates the impact of the project.

B. The Draft SEIS Does Not Support Its Assertions Regarding New Gas Generation Displacing Existing Coal and Oil Use

The SEIS argues that emissions resulting from burning gas delivered by the pipeline will be partially "offset" by reductions in emissions from other fossil fuel sources, which will retire once power plants supplied by the new pipelines are online. SEIS at 2-4; *see also* FEIS at 3-291 to 3-292. However, the SEIS does not demonstrate that retirement of other fossil fuel sources is caused by, or would not occur without, the pipeline project. The discussion of purported offsets is therefore at best tangential to the NEPA obligation to provide a basis for choosing among alternatives, including deciding between the action and no-action alternatives. It is not enough to juxtapose past conditions with a future in which the pipeline project is built: instead, informed decisionmaking requires comparing future scenarios with and without the pipeline project.

The SEIS's discussion of general trends in Florida generation capacity illustrates the need to use a no-action future case, rather than the past, as a basis for evaluating impacts. The SEIS

[5] https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator

states that over the next five years, Florida is projected to retire 4,100 megawatts of capacity, mostly coal, while adding 5,561 megawatts, mostly gas and solar. SEIS at 2. As a threshold matter, the SEIS understates foreseeable additions, which amount to at least 7,309 megawatts.[6] The SEIS also fails to explain why a five-year timeframe was chosen, or the factual basis for these projections.[7] Most importantly, the SEIS provides no discussion of whether the anticipated 2,718 MW of coal retirements are contingent on replacement with substitute capacity. It is likely that they are not: many of Florida's old coal units operate infrequently. Daniel Decl. at ¶ 15.[8] Thus, the SEIS provides no basis for concluding that projected coal retirements would not occur absent new generation. Nor does the SEIS provide a basis for concluding that, even if retirements *are* contingent on replacement with additional generation, that this generation must be new gas facilities. The SEIS recognizes a large projected increase in renewables. SEIS at 2. The SEIS provides no basis for concluding that, if the Southeast Market Pipelines Project was not approved and new gas generation fell below the projected amount, any shortfall would not be met by additional renewables, rather than forgone coal retirement. *See* Daniel Decl. ¶ 17. The SEIS's

[6] The SEIS states that the Okeechobee plant is omitted from the projected capacity increase because it is already in operation, SEIS at 2 n.2, but this plant is neither fully constructed nor in operation. *See* https://www.fpl.com/landing/new-energy.html?cid=aliasaffordablecleanenergy ("Plant construction is expected to take nearly two years (2017-2019) before the facility begins generating power for customers in June 2019."), attached as Exhibit 1; *see also* FEIS at 3-292 (expected to be online in 2019). In addition, the Okeechobee plant is now planned to be larger than contemplated in the FEIS: the FEIS describes the plant as 1600 MW of capacity, FEIS at 3-292, but in January 2017, Okeechobee disclosed plans to increase capacity to 1,748 MW. Florida Power and Light Company letter to Florida Public Service Commission (January 20, 2017), attached as Exhibit 2. FERC's estimates of emissions from this plant must reflect the current proposal.

[7] The SEIS cites "Velocity Suite, ABB" in footnotes 1 and 3, but the public does not appear to have readily available access to this source. The Sierra Club submitted a Freedom of Information Act request on October 13, 2017, which the agency refused to expedite despite this impending comment deadline.

[8] Attached as Exhibit 3.

discussion of statewide trends therefore does not indicate that emission increases resulting from combustion of gas delivered by the pipeline will be "offset" by decreases in other emissions, because the SEIS provides no basis for concluding that those decreases would not occur even if the pipeline was not approved.

FERC's discussion of the particular power plants here also does not support the claimed level of offsets. Although the SEIS makes no particular claim for offsets for the Okeechobee plant, the FEIS asserts that "the planned FPL Okeechobee Plant is part of FPL's strategy to replace older, less efficient power plants with modern, more efficient natural gas-fired facilities." FEIS at 3-292. However, neither the FEIS nor the SEIS address whether, if FERC rejected the proposed pipeline project, FPL would extend use of coal plants or instead would adopt an alternative source of substitute generation, such as renewables.

As to the SEIS's attribution of a 3.87 MMt/y CO_2e reduction to the "Duke Energy Citrus County coal retirement change," SEIS at 3, the SEIS must explain how this reduction can be squared with the FEIS's identification of the Citrus plant as one that would not "directly offset[] GHG emissions from higher intensity sources (i.e., source that emit more GHGs per unit of electrical power generated)." FEIS at 3-298. The FEIS notes that Duke Energy Florida plans to retire two coal generation units at the Crystal River Energy Complex when the Citrus gas project is complete, FEIS at 3-292, but neither the FEIS nor SEIS undertakes any inquiry into whether, if FERC rejected the pipeline project and this led Duke Energy Florida not to build the Citrus gas units, whether Duke would retire the coal units anyway. *See* Daniel Decl. ¶¶ 15, 17 (explaining that Crystal River units 1 and 2 are already minimally dispatched for much of the year).

Finally, even if, in finalizing the SEIS, FERC adds support for the offsets identified in Table 1, these offsets should be applied to the "full burn" emission estimate, not the "total" or "gross" estimate. As explained above, the "total" estimate is unsupported; this remains the case when offsets are considered. Thus, if the final SEIS provides support for the purported 6.14 MMt/y of offsets, the SEIS should identify the "net" downstream impact as 15.96 MMt/y, not 8.36. SEIS at 4.

III. The Draft SEIS Fails to Meaningfully Discuss the Significance of Greenhouse Gas Emissions

The SEIS makes no attempt to satisfy the D.C. Circuit's instruction to provide "a discussion of the 'significance' of" indirect greenhouse gas emissions, or their cumulative impact. *Sierra Club*, 867 F.3d at 1374. The SEIS simply provides estimates of the amount of downstream combustion emissions without *any* discussion of the significance of these emissions or explanation for FERC's determination that these impacts are insignificant. SEIS at 2.

Although the SEIS does not explicitly explain this omission, the SEIS implies that FERC believes discussion of significance requires "measur[ing] the actual incremental impacts of a project on the environment" and that such measurement is impossible here. SEIS at 4-5. To be clear, extensive peer-reviewed literature documents the "discrete environmental effects [of] GHG emissions," including "localized or regional impacts." *Id.* Indeed, the U.S. Global Change Research Project recently again confirmed and quantified a broad range of environmental impacts resulting from greenhouse gas emissions,[9] including discussing how changes in temperature, rainfall, and flood risk from sea level rise will vary for individual regions in the United States.[10] FERC must explain how its conclusion that it is impossible to "attribute discrete environmental

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[9] U.S. Global Change Research Program, 2017: Climate Science Special Report: Fourth National Climate Assessment, Volume I, doi: 10.7930/J0J964J6 (Nov. 3, 2017), *available at* https://science2017.globalchange.gov/downloads/CSSR2017_FullReport.pdf and attached as Exhibit 4. This updates a prior report summarized in the FEIS at 3-296.
[10] *See, e.g.*, *id.* at 334.

effects to GHG emissions" can be squared with these tools and methods. SEIS at 4.

Insofar as the SEIS is referring to attributing these impacts to an individual project's incremental emissions, SEIS at 4, the SEIS's implication that assessment of the physical impact that would result from the project's emissions is both impossible and essential is wrong on both counts. On the first point, greenhouse gas emissions are largely interchangeable—an additional 20 million tons of carbon dioxide emitted in 2025, for example, will have the same impact regardless of whether it is emitted as a result of the SMP Project or as a result of some other activity elsewhere in the world. Accordingly, even if the "scale and complexity" of global climate models precludes modeling two scenarios that differ by the amount of emissions at issue here (*e.g.*, 22.1 MMt/y), SEIS at 4, FERC provides no reason why the impact of SMP Project emissions cannot be interpolated from comparisons of more divergent emission scenarios. Indeed, this type of comparison and interpolation was used to develop the Interagency Working Group's social cost of carbon protocol.[11] Thus, FERC has not demonstrated that it would be impossible or exorbitantly expensive to provide a reasonable prediction of nanometers of sea level rise or fractions of a degree of temperature increase attributable to the SMP Project's incremental emissions. 40 C.F.R. § 1502.22(a).[12]

But the SEIS is further and more fundamentally mistaken in suggesting that such forecasts are essential, or even useful, to NEPA analysis. Climate change is the quintessential cumulative impact problem, and the individual physical changes that will result from any particular action

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[11] Social Cost of Carbon 2010, https://obamawhitehouse.archives.gov/sites/default/files/omb/inforeg/for-agencies/Social-Cost-of-Carbon-for-RIA.pdf, attached as Exhibit 5, at 24-25.

[12] Alternatively, if FERC concludes that forecasting physical changes is impossible, even if FERC is right, need to use "generally accepted" methods to assess, and social cost is such a method. 40 C.F.R. 1502.22(b)(4).

will inevitably appear insignificant to the public. Just as the public and decisionmakers "cannot be expected to convert curies or mrems into such costs as cancer deaths," the SEIS's readership cannot be expected to understand whether an individual project's miniscule marginal increase contribution to increased temperature, sea levels, *etc*. is cause for concern. *Natural Res. Def. Council, Inc. v. U. S. Nuclear Regulatory Comm'n*, 685 F.2d 459, 487 n.149 (D.C. Cir. 1982) *rev'd on other grounds sub nom. Baltimore Gas & Elec. Co. v. Natural Res. Def. Council, Inc.*, 462 U.S. 87, 106-107 (1983). Because individual contributions to climate change are so small, but the cumulative problem is so large, meaningfully disclosing the impact of greenhouse gas emissions requires some tool beyond merely identifying physical changes in the environment attributable to an individual project's emissions.

The most appropriate tool is the protocol developed by the Interagency Working Group on the Social Cost of Greenhouse Gases ("IWG").[13] NEPA does not, of course, require agencies to monetize adverse impacts in all cases. *See* 40 C.F.R. § 1502.23. NEPA does, however, require FERC to take a hard look at the "ecological …, aesthetic, historic, cultural, economic, social, [and] health," effects of its actions, "whether direct, indirect, or cumulative." 40 C.F.R. § 1508.8. Monetization of costs may be required where available "alternative mode[s] of [NEPA] evaluation [are] insufficiently detailed to aid the decision-makers in deciding whether to proceed, or to provide the information the public needs to evaluate the project effectively." *Columbia Basin Land Prot. Ass'n v. Schlesinger*, 643 F.2d 585, 594 (9th Cir. 1981). In another recent case concerning an energy infrastructure project, where the agency's NEPA analysis quantified

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[13] Sierra Club, together with Environmental Defense Fund, Institute for Policy Integrity at New York University School of Law, Natural Resources Defense Council, and Union of Concerned Scientists, is concurrently submitting a separate comment specifically addressing the social cost of carbon. That comment supplements the arguments Sierra Club makes here.

greenhouse gas emissions but claimed that it was impossible to discuss the effects thereof, the court ruled that the agency's refusal to use the social cost of carbon to illustrate the impact of these emissions was arbitrary and capricious. *High Country Conservation Advocates v. United States Forest Serv*., 52 F. Supp. 3d 1174, 1190-91 (D. Colo. 2014).

The IWG's tools remain "generally accepted in the scientific community," 40 C.F.R. § 1502.22(b)(4), notwithstanding Executive Order 13,783, which disbanded the Interagency Working Group and formally withdrew its technical support documents.[14] Indeed, that Executive Order did not find fault with any component of the IWG's analysis. To the contrary, it encourages agencies to "monetiz[e] the value of changes in greenhouse gas emissions" and instructs agencies to ensure such estimates are "consistent with the guidance contained in OMB Circular A-4."[15] The IWG tool, however, illustrates how agencies can appropriately comply with the guidance provided in Circular A-4: OMB participated in the IWG and did not object to the group's conclusions. As agencies follow the Circular's standards for using the best available data and methodologies, they will necessarily choose similar data, methodologies, and estimates as the IWG, since the IWG's work continues to represent the best estimates presently available.[16] Thus, the IWG's 2016 update to the estimates of the social costs of greenhouse gases remains the best available and generally accepted tool for assessing the impact of greenhouse gas emissions, notwithstanding the fact that this document has formally been withdrawn.[17]

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[14] Exec. Order. No. 13,783 § 5(b), 82 Fed. Reg. 16,093 (Mar. 28, 2017).
[15] *Id.* § 5(c).
[16] Richard L. Revesz et al., *Best Cost Estimate of Greenhouse Gases*, 357 SCIENCE 6352 (2017) (explaining that, even after Trump's Executive Order, the social cost of greenhouse gas estimate of around $50 per ton of carbon dioxide is still the best estimate), available at http://policyintegrity.org/files/publications/Science_SCC_Letter.pdf and attached as Exhibit 6.
[17] U.S. Interagency Working Group on the Social Cost of Greenhouse Gases (IWG), "Technical support document: Technical update of the social cost of carbon for regulatory impact analysis

The SEIS provides three reasons for failing to use the social cost of carbon, none of which are supported.[18] Contrary to the SEIS's assertion, the estimates of social cost do "measure actual incremental impacts of a project on the environment." SEIS at 5. The social cost tools are built on models of impacts to temperature, sea level rise, ecosystem services, and other physical impacts, together with assessments of how these physical changes will impact agriculture, human health, *etc*. The social cost protocol then identifies the social cost imposed by a ton of emissions' pro rata contribution to these environmental problems. As explained above, this either amounts to an assessment of physical impacts or the best available generally accepted alternative to such an assessment; either way, the tool is appropriate for use under NEPA. 40 C.F.R. § 1502.22(b)(4). Nor is lack of consensus as to a single most appropriate intergenerational discount rate a reason for refusing to use the social cost protocols. SEIS at 5.[19] As the 2010 Technical Support Document explained, a range of three discount rates—2.5, 3, and 5 percent—"reflect reasonable judgments" and "span a plausible range" of appropriate discount rates, and are consistent with

under executive order 12866 & Addendum: Application of the methodology to estimate the social cost of methane and the social cost of nitrous oxide" (August 26, 2016), *available at* https://obamawhitehouse.archives.gov/sites/default/files/omb/inforeg/scc_tsd_final_clean_8_26_16.pdf and attached as Exhibit 7.

[18] These arguments simply repeat without elaboration the position FERC took in *EarthReports, Inc. v. Fed. Energy Regulatory Comm'n*, 828 F.3d 949, 956 (D.C. Cir. 2016). In *Sierra Club*, the D.C. Circuit instructed FERC to explain "whether the position on the Social Cost of Carbon that the agency took in *EarthReports* still holds, *and why*." *Sierra Club*, 867 F.3d at 1375 (emphasis added). *EarthReports* held that, in an environmental assessment, FERC was not required to use the social cost of carbon to address the impact of greenhouse gases directly emitted by project construction and operation. Here, FERC is undertaking a more searching review (environmental impact statement) of the impact of a much larger volume of emissions (indirect annual emissions of up to 22.1 million tons, compared to less than 2 million tons in *EarthReports*). Even putting these unacknowledged differences aside, available evidence rebuts the SEIS's specific arguments regarding social cost of carbon, as we explain herein.

[19] The SEIS cites an EPA fact sheet for the proposition that there is no such consensus; we note that this document is no longer available.

OMB Circular A-4.[20] Indeed, the Circular provides a general recommendation for a 3 percent rate; although the Circular also identifies 7 percent rate as appropriate for use in other circumstances, the Circular itself indicates that the 7 percent figure should not be used when assessing impacts like climate change that will affect the public as a whole, and OMB, together with the rest of the Interagency Working Group, has explicitly affirmed that the 7 percent rate is inappropriate when addressing climate change.[21] Thus, as explained by the IWG, uncertainty as to the most appropriate discount rate is a reason to provide social cost estimates using the range of plausible rates—which FERC and other agencies have done in other proceedings[22]—but it is not a reason for ignoring the social cost of greenhouse gas emissions entirely. *Ctr. for Biological Diversity v. Nat'l Highway Traffic Safety Admin.*, 538 F.3d 1172, 1200 (9th Cir. 2008) (disagreement over cost of carbon emissions does not allow agency to forego estimating cost where, "while the record shows … a range of values, the value of carbon emissions reduction is certainly not zero.").[23]

Finally, the SEIS argues that the social cost of carbon "is not appropriate for use in any project-level NEPA review" because "there are no established criteria identifying the monetized

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[20] IWG 2010 Social Cost of Carbon TSD at 17-18, 23.

[21] Interagency Working Group on the Social Cost of Carbon, *Response to Comments: Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12,866* at 36 (July 2015), available at https://obamawhitehouse.archives.gov/sites/default/files/omb/inforeg/scc-response-to-comments-final-july-2015.pdf and attached as exhibit 8.

[22] *See, e.g.,* FERC, Final EIS, Constitution Pipeline and Wright Interconnect Projects, CP13-499 (Oct. 2014), Accession No. 20141024-4001, at 4-256 to 4-257 ("For 2015, the first year of project operation, … the project's social cost of carbon for 2015 would be $1,638,708 at a discount rate of 5 percent, $5,325,802 at 3 percent, and $8,330,100 at 2.5 percent.").

[23] As explained in Sierra Club's concurrently filed joint comment, a growing body of literature suggests that the discount rate used for assessing climate harms should be lower than 3 or even 2.5 percent, reflecting both the decline in general interest rates since Circular A-4 was adopted and the particular nature of climate harms. Using a lower discount rate would *increase* the estimate of the social cost of carbon; thus, the IWG estimates do not risk overstating impacts.

values that are to be considered significant for NEPA reviews." SEIS at 5. The point of addressing "significance" in an Environmental Impact Statement is to inform the public and agency decisionmaking, not to simply label impacts as "significant" or "insignificant." Here, the SEIS must help the public and FERC understand whether the adverse consequences of the SMP Project's greenhouse gas emissions (direct and indirect) are severe enough to warrant consideration in the public interest analysis, and, indeed, whether these emissions tip the balance toward the conclusion that the project is contrary to, and not required by, the public convenience and necessity. The current SEIS provides no information to use in answering these questions; it is indisputable that estimating the impacts of emissions using the social cost protocols would speak to these issues, regardless of whether FERC concludes that the monetized impact is or is not significant. Although FERC has discretion to choose among reliable methodologies for evaluating impacts, that discretion does not allow FERC to provide no evaluation whatsoever when a generally accepted methodology is available. 40 C.F.R. § 1502.22(b)(4), *see also N. Plains Res. Council, Inc. v. Surface Transp. Bd.*, 668 F.3d 1067, 1085 (9th Cir. 2011) (holding that agency decision not to survey for wildlife prior to approving project was not a valid exercise of discretion as to assessment methodology).

Thus, estimating social cost is a generally accepted method, consistent with OMB Circular A-4, to provide otherwise absent information about the severity and impact of the project's greenhouse gas emissions. Even putting this method aside, however, the SEIS's implicit conclusion that a nearly 10% increase in Florida's greenhouse gas emissions are insignificant is implausible. In general, because climate change is a cumulative problem, comparison to existing inventories is not an effective method of assessing the importance of greenhouse gas emissions: any one project's contributions will inevitably appear small when measured against the cumulative total. Here, however, if such comparisons are going to be made, the appropriate denominator is emissions in Florida, because all indirect emissions are expected to occur there. *Increasing* emissions by nearly ten percent will self-evidently interfere with the drastic emission *reductions* necessary to avoid catastrophic climate change. As affirmed just this month by the Fourth National Climate Assessment, without "[w]ithout major reductions in [greenhouse gas] emissions, the increase in annual average global temperatures relative to preindustrial times could reach 9°F (5°C) or more by the end of this century," with disastrous consequences.[24]

Other non-monetized comparisons similarly illustrate the startling scale of the project's indirect emissions. These are startling numbers for a single project. According to the EPA's greenhouse gas equivalencies calculator, 22,100,000 metric tons of CO_2 or CO_{2e} is equivalent to the GHG emissions from 4,732,334 passenger vehicles driven for one year, or to the CO_2 emissions from 5.5 coal-fired power plants in one year.[25] For an alternative comparison, Florida's six largest emitters of CO_2 within the electric power sector in 2016 were all coal units; that year, they collective emitted 20.3 million metric tons of CO_2. Daniel Decl. at ¶18.

The SEIS also fails to discuss cumulative impacts. Instead of providing the discussion and analysis required by the court's order, FERC simply states that it "could not find a suitable method to attribute discrete environmental effects to GHG emissions" and that it is "not aware of a tool to meaningfully attribute specific increases in global CO2 concentrations, heat forcing, or similar global impacts to SMP Project GHG emissions." SEIS at 4-5. FERC's failure to identify such a tool does not excuse the fatal flaws contained in the SEIS – *i.e.*, the failure to discuss the significance of this massive increase in GHG emissions, or assess their cumulative impact.

[24] CSSR report at 15.
[25] https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator

(Despite the court's admonition to discuss the significance and cumulative impact of downstream emissions, the words "significance" and "cumulative impact" do not even appear in the "Greenhouse Gas Emissions" section of the SEIS.)

IV. Conclusion

For the reasons stated above, the draft SEIS fails to provide the analysis required by NEPA and by the D.C. Circuit's order in *Sierra Club*. FERC must prepare additional analysis to correct and clarify the estimates of the amount of indirect emissions, and FERC must discuss the significance and cumulative impact of these emissions.

Sincerely,

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CERTIFICATE OF SERVICE

I hereby certify that I have this day served the foregoing document upon each person designated on the official service list compiled in this proceeding.

Dated at Oakland, CA this 20th day of November, 2017.

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Powering Florida's growing population and economy

At FPL, we invest continuously in our electric system to ensure we can provide our customers with a reliable supply of affordable, clean energy – 24 hours every day – now and in the future.

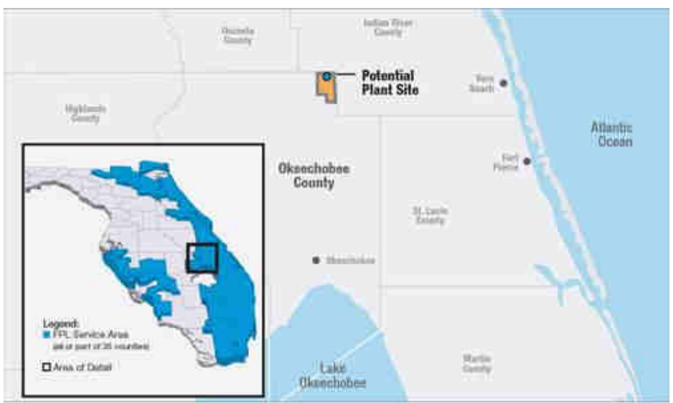
We serve our customers using a diverse mix of resources, including energy efficiency, wholesale electricity purchased from non-FPL power generators and FPL's advanced fleet of power-generation facilities fueled by natural gas, solar, nuclear and other sources.

To ensure we can continue to meet our customers' future energy needs, we conduct ongoing, in-depth planning. Based on our annual forecast filed with the Florida Public Service Commission (PSC) in 2014, we projected a need for more than 1,000 megawatts of additional power generation beginning in 2019 – and more in the years that follow.

Our projected need for additional power takes into account substantial energy conservation and FPL's three new large-scale solar plants, which began operating in 2016. We're also building eight additional large-scale solar facilities scheduled to operate by early 2018.

To meet Florida's growing energy needs, FPL is building the Okeechobee Clean Energy Center, a high-efficiency power-generating facility fueled by clean, U.S.-produced natural gas. It is located on FPL-owned property in northeast Okeechobee County. The new facility – one of the cleanest, most efficient of its kind in the world – will also produce enormous economic benefits for the area.

We continue to share information with public officials, the local community and interested stakeholders throughout the construction of the Okeechobee Clean Energy Center.



Why more power is needed +

How we're meeting Florida's growing energy needs +

New clean energy center +

Major economic benefits +

Protecting the environment

+

Current schedule

−

FPL’s Okeechobee Clean Energy Center successfully completed comprehensive reviews by numerous Florida, county, regional and federal agencies in 2016 – see the list below. Plant construction is expected to take nearly two years (2017-2019) before the facility begins generating power for customers in June 2019.

Frequently Asked Questions (FAQs)

+

FPL

January 20, 2017

Mr. Andrew Maurey, Director
Division of Accounting & Finance
Florida Public Service Commission
2540 Shumard Oak Boulevard
Tallahassee, Florida 32399

Re: Construction of Okeechobee Clean Energy Center (OCEC) - Docket No. 150196-EI

Dear Mr. Maurey:

In accordance with Order No. PSC-16-0032-FOF-EI, the need determination order for OCEC in the above-referenced docket, Florida Power & Light Company ("FPL") is providing the current budgeted and actual costs, compared to the estimated total in-service costs for OCEC that were relied upon in the need determination.

Cost Category	Okeechobee Estimate Approved in Need Determination ($MM)	Okeechobee Actual to Date Cost as of December 31, 2016 ($MM)	Okeechobee Estimated Total In-Service Cost as of December 31, 2016 ($MM)
Power Block	1,056.3	415.4	1,049.1
Land	-	0.4	0.4
Transmission, Interconnection, and Integration	52.0	0.1	52.0
AFUDC	123.4	7.7	130.2
Total Plant Cost	1,231.7	423.6	1,231.7

Construction of the OCEC unit began in December, 2016. Since the time of the need determination, FPL has continued to work with its vendors to evaluate ways in which OCEC could be made even more beneficial for customers. FPL has identified upgrades to OCEC that are expected to increase the summer peak rating from about 1,633 MW to about 1,748 MW and improve the unit's operating efficiency, while remaining within the original estimated total plant cost of $1,231.7 million. FPL will continue to update the Commission on an annual basis and will continue to strive to maximize benefits to customers in a prudent and reasonable fashion.

Please contact me if you have any questions.

Sincerely,

Korel M. Dubin

Korel M. Dubin
Director, Regulatory Affairs

DECLARATION OF JOSEPH M. DANIEL

1. My name is Joseph Daniel, I am currently employed by the Sierra Club where I serve as an Electric Sector Analyst and have been in this position for nearly two years. In this capacity I have performed technical and economic analysis of the ten-year site plans of Florida's major utilities, including Florida Power and Light (FPL) and Duke Energy Florida. As the point person for internal analysis in the southeastern region, which includes Florida, I've also served as a technical consultant and reviewer on many other comments submitted by the Sierra Club on dockets concerning Florida's electric utilities as well as other state electric utility dockets in the region. My duties also include serving as the lead analyst on a number of issues including analysis of federal energy and environmental policy; fossil fuel economics; and analysis of the natural gas sector.

2. I have a B.S. from Florida Institute of Technology in Chemical Engineering (2006) and M.P.A. from Columbia University's School of International and Public Affairs in Environmental Science and Policy (2012). I also have a certificate from the University Of Texas at Austin on Petroleum Fundamentals (2007). I have over a decade of experience working on energy related issues from both technical and financial perspectives. I began my career in 2006 as an engineer at oil refineries. Immediately prior to joining the Sierra Club in 2016, I was a consultant at Synapse Energy Economics, a research and consulting firm that specializes in energy,

environmental, and electricity sector issues and policies, including fossil fuel generation. There I served as one of the firm's technical experts on utility planning, energy modeling, integrated resource planning, and economic forecasting. I've also authored many publications including an article on the risks of pipeline overdevelopment published in Natural Gas and Electricity. My CV and a full list of my publications can be found as an attachment to this declaration.

3. I have been asked to perform a technical review of the declarations submitted by Intervenors Duke Energy Florida, LLC et al. with their petition for rehearing en banc. My review focuses on whether there would be reliability or critical capacity issues, i.e. a disruption to natural gas and electricity service to Florida consumers from a temporary cessation of the delivery of natural gas through the Southeast Market Pipelines to comply with the court's vacatur of the FERC certificate. Or, in the words of Intervenors' petition at p. 2, whether this would "cause severe disruption ... for millions of Florida residents who rely on electricity generated at plants served by the pipelines." As set forth below there should not be serious reliability concerns or any interruption of service to consumers.

4. In connection with this I have reviewed the Intervenors' declarations of Shammo, Sideris, Stubblefield, Macon, and Duvall, along with publicly available data on Florida Power & Light Company's (FPL) electric system including

historical load profiles and generation patterns of coal and gas assets using data from EIA and S&P Global Market Intelligence. I have also reviewed available operational data on the Gulfstream and Florida Gas Transmission (FGT) pipelines using S&P Global Market Intelligence. Additionally, I reviewed the ten-year site plans of Duke Florida and FPL, as well as the "Regional Load and Forecast Plan" of the Florida Reliability Coordinating Council (FRCC). I also reviewed North American Electric Reliability Corporation (NERC) and Federal Energy Regulatory Commission (FERC) reliability reports.

5. The Intervenors' own declarations indicate that there would be no "severe disruption," i.e. no interruption of electrical service for any Florida residents. None of the declarations conclude there would be any blackouts or loss of service and none of the declarants offer any evidence into the record that conclude that there would be meaningful service disruptions (i.e. blackouts or interruption of service) caused by a temporary halt of pipeline operations. Rather they indicate the grid would rely on a combination of increased use of existing power plants, including coal units, oil units, or gas units currently being served by existing gas pipelines. See e.g., Stubblefield declaration at ¶4.

6. This lack of interruption of electrical service is consistent with my own research concerning whether a temporary interruption in operation of the Southeast Market Pipeline (SMP) would cause reliability problems in Florida. Contrary to the

claim that "FPL is still in its peak demand season," (Stubblefield at ¶7) FPL is not in peak demand season, rather it is leaving high demand season and entering low demand season. Since 2012, FPL and Duke's system peak have only occurred in June, July, or August.[1] Both Florida's peak gas demand and the state's peak electric demand occur in the summer and are driven by electric sector load (which is driven by air conditioning load, which peaks in the summer). Fall, winter, and early spring months are lower load months for Florida, both in terms of overall gas demand and electric demand. Based on the Energy Information Agency, a part of the U.S. Department of Energy that "collects, analyzes, and disseminates independent and impartial energy information," Florida's October gas consumption is typically about at average levels (October 2016 was 0.1% above 2016 monthly average, October 2015 was 2% above 2015 monthly average).[2] In both 2015 and 2016, January, February, March, November, and December were the months with the lowest monthly gas consumption for the electric power sector.[3] Florida's gas consumption in August 2016 was at its peak and was 57% higher than consumption in the lowest month that year, November.[4] If existing gas

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[1] Data compiled by S&P Global Market Intelligence
[2] Calculations are my own based on data from EIA form 923. EIA-923 data for 2016 is still in "early release" form and not finalized.
[3] Id.
[4] Id.

infrastructure can serve the needs of this past summer, then it can likely meet the needs of this forthcoming winter.

7. In fact, Florida has plenty of excess generation capacity to meet future demands. The North American Electric Reliability Corporation (NERC) assesses the electric grid's ability to meet load by assessing changes in demand and load serving resources. NERC identifies a reference reserve margin for the FRCC (the reliability region which includes all of Duke Florida's and FPL's territory and most of Florida) as 15 percent; Florida's investor owned utilities have a voluntary reserve margin of 20 percent.[5] NERC's most recent estimates indicate that this winter the FRCC region will have a winter reserve margin of nearly 40 percent.[6]

8. Intervenors' declarations also claim risks of additional reliability impacts from discontinuing operation of Sabal Trail's Central Florida Hub, which currently allows for pipeline transportation hub service among Sabal Trail, Florida Southeast, and Gulfstream Natural Gas System and also will connect to the fourth interstate pipeline in the central and south Florida regions (Florida Gas Transmission Company, LLC). The declarants claim that the hub is currently

[5] FRCC. "Florida Public Service Commission 2017 Ten-Year Site Plan Workshop FRCC Presentation." September 12, 2017. Available online at: http://www.psc.state.fl.us/Files/PDF/Utilities/Electricgas/TenYearSitePlans/2017/FRCC_Presentation.pdf

[6] FERC. "Winter 2017-18 Energy Market Assessment." Docket No. AD06-3, Item No. A-3. October 19, 2017. Available online at: https://www.ferc.gov/market-oversight/reports-analyses/mkt-views/2017/10-19-17-A-3.pdf

providing important supply reliability and flexibility benefits for natural gas-fired electric generation connected to the pipeline grid in these regions by focusing on firm capacity availability on the existing pipelines (see Shammo at ¶10 and ¶16; Stubblefield at ¶5 and ¶7; and Macon at ¶8). Availability of contractible firm capacity is not, however, indicative of available space on a pipeline to procure gas. Industry wide, most gas is not procured on firm capacity contract, rather on spot purchases.[7] As detailed below, Florida's two major pipelines have plenty of availability for power plants to procure more gas.

9. According to Intervenors' declarations, of the two other interstate natural gas pipelines that provide service into central and southern Florida (Gulfstream Natural Gas System, LLC and Florida Gas Transmission, LLC), only one has available firm and uncommitted capacity, which is limited to only approximately 97,000 Dth/d, just 2% of total capacity with deliverability into central Florida. Intervenors assert that this is insufficient to cover the firm capacity being provided by the Sabal Trail Project and suggest that without more firm capacity, natural gas power plants will not be able to procure the gas needed to meet electric demand. The declarants' fixation on firm capacity is misleading. FGT is three times the size of SMP and Gulfstream is 1.3 times the size of SMP (both in terms of capacity). Historically, both FGT and Gulfstream have been underutilized, even during

[7] Based on "Fuel Receipt Data" from EIA-923

Florida's peak demand days. I analyzed the utilization of both pipelines between January 1, 2014 and December 31, 2016 (the three calendar years prior to SMP operation) using data compiled by S&P Global Market Intelligence, and found that FGT's average utilization at power plant delivery points was 28 percent and peak utilization was 40 percent. Similarly, Gulfstream's 3-year average utilization rate for power plant deliveries was 36 percent, with a peak utilization of 49 percent. Using that same data, and comparing to data on annual peak load for the Duke Energy Florida system and the FPL system, I found that on no utility system peak day did either pipeline have a utilization rate above 48 percent. Below I have included a table of the dates when Duke Energy Florida's and FPL's systems have respectively peaked and the corresponding utilization rate of each major pipeline on that same date.

Year	Utility	Date of Utility System Peak	FGT Utilization Percent on Date	Gulfstream Utilization on Date
2014	Duke Energy Florida	7/28/2016	40%	44%
	Florida Power & Light	7/6/2016	35%	41%
2015	Duke Energy Florida	8/25/2015	40%	44%
	Florida Power & Light	6/22/2015	40%	43%
2016	Duke Energy Florida	8/21/2014	38%	48%
	Florida Power & Light	7/28/2014	36%	44%

10. Intervenors also point out that Florida has no natural gas storage (Stubblefield at ¶3 and Shammo at ¶10), suggesting that in the absence of storage, that additional pipeline capacity is necessary to maintain reliability. This statement is misleading because utilities in Florida have contracts for out-of-state gas storage with the ability to withdraw 0.94 Billion cubic feet per day.[8]

11. Intervenors' declarations state that it would take 12-18 months to get the pipeline up and running after a shutdown (Shammo at ¶14). However, Phase 1 of the Sabal Trail Transmission project only took approximately nine months to construct, and once construction was completed, only took one month to start delivering gas.[9] The declarations are suggesting that it will take longer to bring a pipeline back online than it took to construct and bring it into service in the first place.

12. Some of the declarants lay out claims of economic harms in the form of lost tax revenue, economic output, and wages. For example, Shammo at ¶17 identifies

[8] FRCC. "Florida Public Service Commission 2017 Ten-Year Site Plan Workshop FRCC Presentation." September 12, 2017. Available online at: http://www.psc.state.fl.us/Files/PDF/Utilities/Electricgas/TenYearSitePlans/2017/FRCC_Presentation.pdf

[9] Based on claims made on the Sabal Trail Transmission website which states that Phase 1 was scheduled to "[C]ommence in June 2016 and be completed by March 2017" which is nine months (http://www.sabaltrailtransmission.com/faq). Subsequent press reports confirm that the construction was completed nine months after it began (http://www.mypalmbeachpost.com/business/just-fpl-pipeline-done-but-when-will-pump-natural-gas/mMniGRWI0xJT4LqUI9B53N/). Construction was completed in May and began delivering fuel in June.

$1.4 billion in potential ad valorem tax revenue across Alabama, Georgia and Florida states, which seems to be inclusive of the $262 million in ad valorem tax revenue Macon at ¶11 identifies for Florida. However, both of these values would have been accrued over a 60-year time horizon; therefore the declarant's are over-estimating the *costs* (in the form of potential lost revenue) by 3,900 percent to 23,900 percent.[10]

13. Moreover, some of the supposed costs identified by the declarants are not genuine economic costs rather they are either sunk costs or internal transfer of funds. The developers of Sabal have already spent the money for constructing it, these costs are sunk, and are not new costs as suggested by Shammo at ¶13, Shammo at ¶15, and Macon at ¶12. To suggest that those costs are somehow newly incurred costs precipitated by a delay in pipeline operation is disingenuous and roughly equivalent to claiming that paying your credit card bill is a cost, when in reality paying of debt doesn't not change your net worth. Macon at ¶7 discusses how Nextera may have to pay FPL for failure to deliver firm capacity, however FPL is owned by Nextera, this isn't a cost so much as it is an internal transfer of funds. If I transfer money from one bank account to a separate bank account (both of which are in my name), my net worth has remained the same.

[10] Range based on assuming an 18-month delay versus assuming a 3-month delay.

14. Intervenors' declarations also state that without the Southeast Market Pipeline (SMP) Project, Duke cannot begin bringing online its new Citrus County Combined Cycle Project, a gas plant needed to meet peak load "in the immediate future." Shammo at ¶11 cites to similar needs to meet "rapidly expanding" load, and Macon at ¶9 points to the need of a different gas plant, Okeechobee Clean Energy Center, to serve local load. These claims are supported by no evidence and as established earlier, ignore the excess generation and pipeline capacity that already exists within Florida. It is also worth noting that the growth rate in the region has slowed considerably and is currently only at about 1% per year.[11] Consequently, claims of "immediate need" to meet "rapidly expanding" demand are overstated.

15. The Intervenors' declarations are also misleading on whether a temporary interruption in operation of the Southeast Market Pipeline would have adverse environmental impacts in the form of delayed retirements of coal facilities like Cedar Bay (Stubblefield at ¶4), Indiantown (Stubblefield at ¶4), or Crystal River Units 1 & 2 (Sideris at ¶6). It is worth noting, Cedar Bay is already retired, and it

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[11] FRCC. "Florida Public Service Commission 2017 Ten-Year Site Plan Workshop FRCC Presentation." September 12, 2017. Available online at: http://www.psc.state.fl.us/Files/PDF/Utilities/Electricgas/TenYearSitePlans/2017/FRCC_Presentation.pdf

retired nearly a year ago, on December 31st of 2016.[12] Indiantown generally runs less in the winter / low load months anyways, and it did not run at all between December 2016 and June 2017, the seven months prior to the Pipeline's operational start. Similarly, Crystal River Units 1 and 2 rarely operate in the winter / low load months and last November Crystal River Unit 1 was down November 28, 2016 through March 26, 2017.[13] Similarly, Crystal River Unit 2 operated very little last year; Unit 2 was brought down in September 2016, and through March of 2017 was only brought back up three times.[14]

16. In response to the court's order FERC generated a *draft* "Supplemental Environmental Impact Statement." This is only a draft and the public has until November 20, 2017 to provide written comments on it, after which FERC will presumably issue a final SEIS based on those comments. Sierra Club and others intend to file comments on the SEIS by the due date. Thus, the final SEIS may or may not contain the same findings and conclusions as the draft, and could revise the decisions made in the Final Environmental Impact Statement as to the choice of alternatives and mitigation measures.

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[12] FPL. "FPL shuts down Cedar Bay coal-fired power plant, helping the environment and saving customers more than $70 million." Press Release. December 21. 2016. Available online at: http://newsroom.fpl.com/2016-12-21-FPL-shuts-down-Cedar-Bay-coal-fired-power-plant-helping-the-environment-and-saving-customers-more-than-70-million

[13] Analysis of S&P Global Market Intelligence data

[14] Analysis of S&P Global Market Intelligence data

17. FERC's draft SEIS is flawed and makes several assumptions that result in meaningful underestimations of the emissions impacts of the pipeline. A full assessment and comment period for the draft SEIS is underway and may significantly impact its conclusions. Sierra Club will be preparing separate comments for the draft SEIS, but there are several significant flaws with the draft SEIS including:

- The draft SEIS assumes that gas from the pipeline will go to gas-fired power plants that will displace coal- and oil-fired generation resources. This is based on a trend to retire aging coal and oil facilities.[15] However, as illustrated above, most of these coal units have either already retired or operate infrequently leaving little opportunity for them to be further displaced. If we accept the declarants claims that the gas pipeline is needed to serve new, increasing load, then the gas is actually replacing some other new source of generation, like solar or wind.
- The draft SEIS does not account for methane leakage as a contributor to greenhouse gas estimates. Methane leaks occur downstream of the pipeline at many points including at power plants and at industrial facilities. By excluding these emissions the draft SEIS is effectively assuming that no gas will leak from the system.

[15] Draft SEIS, Page 2

- The draft SEIS uses a 100-year global warming potential (which is a measure of the relative global warming impact of various greenhouse gases) based on the IPCC's 2007 evaluation. However, more recent assessments have increased the relative global warming impacts of greenhouse gases, including methane. Moreover, the draft SEIS doesn't investigate the impacts of using an alternative, 20-year global warming potential value. Either of these adjustments would increase the final estimate of downstream emissions.

18. The report's conclusion, that 22.1 million metric tons per year increase in Florida GHG emissions is "not significant," is flawed not only because that value is a clear underestimation of the overall impacts but also because 22.1 million metric ton per year is, in fact, significant. For reference, Florida's six largest emitters of CO_2 within the electric power sector in 2016 were all coal units; that year, they collectively emitted only 20.3 million metric tons of CO_2.[16] For an alternative comparison, the Environmental Protection Agency offers a greenhouse gas equivalency calculator that allows users to compare emissions numbers in terms of other metrics like vehicles on the road or coal plants. Based on that

[16] Crystal River 5, Crystal River 4, Seminole Unit 1, Seminole Unit 2, St. Johns River Power unit 2, Stanton Energy Center Unit 2. Based on data compiled by S&P Global Market Intelligence.

calculator, 22.1 million metric tons is equivalent to greenhouse gas emissions from 4.7 million passenger vehicles or 5.5 coal plants.[17]

I declare under the penalty of perjury under the laws of the United States that, to the best of my knowledge, the foregoing is true and correct.

DATED: October 31, 2017

Joseph M. Daniel

[17] Available here: https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator

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PROFESSIONAL EXPERIENCE

Sierra Club, Washington, D.C. *Electric Sector Analyst*, 2016 – Present

- Serves as lead analyst on federal policy, natural gas, coal economics, and energy markets.
- Supports the development of junior staff through mentorship and training
- Reviews utility rate cases, integrated resource plans, and long term planning
- Presented analysis and represented organization at academic and industry conferences
- Responsible for conducting economic analysis of federal regulations and market rules
- Builds and maintains databases; constructs economic and technical models for internal use
- Subject matter expert and lead analyst on: fossil fuel economics, markets design, natural gas, long term energy planning, and federal policy.

Synapse Energy Economics Inc., Cambridge, MA. *Associate*, 2013 –2015

- Specialized in reviewing long-term planning and cost-benefit analysis within the energy sector
- Provided recommendations to utility regulator on how to align utility's short- and long-term fuel cost assumptions with industry best practices.
- Led researching efforts and conducted primary analysis on the electric industry including utility forecasting, regulatory compliance, and distributed energy resources
- Conducted economic modeling of distributed energy resources under various utility rate tariffs
- Modeled costs and benefits of energy efficiency and small scale solar in ISO New England using Market Analytics

Independent Consultant, New York, NY. 2011 – 2013

- Wrote executive briefs on the sustainability and economic development efforts of municipalities for the Economic Transformation Group (ETG)
- Analyzed technical and economic drivers for "Green Palm Oil Production" for the ETG
- Co-authored World Bank report: *Kathmandu Valley Cultural Tourism Competitiveness Assessment and Action Plan*
- Designed and developed mathematical models for the STAR Community Index

Environmental Law & Policy Center, Madison, WI. *Policy and Science Intern*, 2011

- Investigated consequences of state policy changes related to wind turbine siting regulations
- Initiated research for a report to quantify jobs created by wind and solar energy industries
- Analyzed regional economic impacts of USDA grant data associated with renewable energy provisions of the 2008 Farm Bill

Tel Aviv – Yafo Municipality, Tel Aviv, Israel. *Research Assistant to Deputy Mayor*, 2010

- Presented urban sustainability case studies (including PlaNYC) and best practices to the mayor, deputy mayor, and city council
- Worked with public- and private-sector partners to define metrics for a governmental Green Business Certification Program
- Investigated US and European greenhouse gas emission reduction policies and programs for application in Tel Aviv

Baker Hughes - Baker Petrolite (Industrial Division), Honolulu, HI. *Engineer II*, 2006 – 2010

- Managed daily operation of the primary account on the island, worth over $1.8 million annually

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- Monitored performance metrics, analyzed project performance, calculated energy and cost savings related to efficiency upgrades
- Consulted with customers on reducing environmental impacts of facilities

EDUCATION

Columbia University – School of International Public Affairs, New York, NY
Master of Public Administration in Environmental Science and Policy, 2012

University of Texas, Austin, TX
PETEX Petroleum Fundamentals Program, 2007

Florida Institute of Technology – College of Engineering, Melbourne, FL
Bachelor of Science in Chemical Engineering, 2006

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Technical Support Document: -
Social Cost of Carbon for Regulatory Impact Analysis -
Under Executive Order 12866 -

Interagency Working Group on Social Cost of Carbon, United States Government

With participation by

Council of Economic Advisers
Council on Environmental Quality
Department of Agriculture
Department of Commerce
Department of Energy
Department of Transportation
Environmental Protection Agency
National Economic Council
Office of Energy and Climate Change
Office of Management and Budget
Office of Science and Technology Policy
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Executive Summary

Under Executive Order 12866, agencies are required, to the extent permitted by law, "to assess both the costs and the benefits of the intended regulation and, recognizing that some costs and benefits are difficult to quantify, propose or adopt a regulation only upon a reasoned determination that the benefits of the intended regulation justify its costs." The purpose of the "social cost of carbon" (SCC) estimates presented here is to allow agencies to incorporate the social benefits of reducing carbon dioxide (CO_2) emissions into cost-benefit analyses of regulatory actions that have small, or "marginal," impacts on cumulative global emissions. The estimates are presented with an acknowledgement of the many uncertainties involved and with a clear understanding that they should be updated over time to reflect increasing knowledge of the science and economics of climate impacts.

The SCC is an estimate of the monetized damages associated with an incremental increase in carbon emissions in a given year. It is intended to include (but is not limited to) changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services due to climate change.

This document presents a summary of the interagency process that developed these SCC estimates. Technical experts from numerous agencies met on a regular basis to consider public comments, explore the technical literature in relevant fields, and discuss key model inputs and assumptions. The main objective of this process was to develop a range of SCC values using a defensible set of input assumptions grounded in the existing scientific and economic literatures. In this way, key uncertainties and model differences transparently and consistently inform the range of SCC estimates used in the rulemaking process.

The interagency group selected four SCC values for use in regulatory analyses. Three values are based on the average SCC from three integrated assessment models, at discount rates of 2.5, 3, and 5 percent. The fourth value, which represents the 95th percentile SCC estimate across all three models at a 3 percent discount rate, is included to represent higher-than-expected impacts from temperature change further out in the tails of the SCC distribution.

Social Cost of CO_2, 2010 – 2050 (in 2007 dollars)

Discount Rate Year	5% Avg	3% Avg	2.5% Avg	3% 95th
2010	4.7	21.4	35.1	64.9
2015	5.7	23.8	38.4	72.8
2020	6.8	26.3	41.7	80.7
2025	8.2	29.6	45.9	90.4
2030	9.7	32.8	50.0	100.0
2035	11.2	36.0	54.2	109.7
2040	12.7	39.2	58.4	119.3
2045	14.2	42.1	61.7	127.8
2050	15.7	44.9	65.0	136.2

I. Monetizing Carbon Dioxide Emissions

The "social cost of carbon" (SCC) is an estimate of the monetized damages associated with an incremental increase in carbon emissions in a given year. It is intended to include (but is not limited to) changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services. We report estimates of the social cost of carbon in dollars per metric ton of carbon dioxide throughout this document.[1]

When attempting to assess the incremental economic impacts of carbon dioxide emissions, the analyst faces a number of serious challenges. A recent report from the National Academies of Science (NRC 2009) points out that any assessment will suffer from uncertainty, speculation, and lack of information about (1) future emissions of greenhouse gases, (2) the effects of past and future emissions on the climate system, (3) the impact of changes in climate on the physical and biological environment, and (4) the translation of these environmental impacts into economic damages. As a result, any effort to quantify and monetize the harms associated with climate change will raise serious questions of science, economics, and ethics and should be viewed as provisional.

Despite the serious limits of both quantification and monetization, SCC estimates can be useful in estimating the social benefits of reducing carbon dioxide emissions. Under Executive Order 12866, agencies are required, to the extent permitted by law, "to assess both the costs and the benefits of the intended regulation and, recognizing that some costs and benefits are difficult to quantify, propose or adopt a regulation only upon a reasoned determination that the benefits of the intended regulation justify its costs." The purpose of the SCC estimates presented here is to make it possible for agencies to incorporate the social benefits from reducing carbon dioxide emissions into cost-benefit analyses of regulatory actions that have small, or "marginal," impacts on cumulative global emissions. Most federal regulatory actions can be expected to have marginal impacts on global emissions.

For such policies, the benefits from reduced (or costs from increased) emissions in any future year can be estimated by multiplying the change in emissions in that year by the SCC value appropriate for that year. The net present value of the benefits can then be calculated by multiplying each of these future benefits by an appropriate discount factor and summing across all affected years. This approach assumes that the marginal damages from increased emissions are constant for small departures from the baseline emissions path, an approximation that is reasonable for policies that have effects on emissions that are small relative to cumulative global carbon dioxide emissions. For policies that have a large (non-marginal) impact on global cumulative emissions, there is a separate question of whether the SCC is an appropriate tool for calculating the benefits of reduced emissions; we do not attempt to answer that question here.

An interagency group convened on a regular basis to consider public comments, explore the technical literature in relevant fields, and discuss key inputs and assumptions in order to generate SCC estimates. Agencies that actively participated in the interagency process include the Environmental Protection

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[1] In this document, we present all values of the SCC as the cost per metric ton of CO_2 emissions. Alternatively, one could report the SCC as the cost per metric ton of carbon emissions. The multiplier for translating between mass of CO_2 and the mass of carbon is 3.67 (the molecular weight of CO_2 divided by the molecular weight of carbon = 44/12 = 3.67).

Agency, and the Departments of Agriculture, Commerce, Energy, Transportation, and Treasury. This process was convened by the Council of Economic Advisers and the Office of Management and Budget, with active participation and regular input from the Council on Environmental Quality, National Economic Council, Office of Energy and Climate Change, and Office of Science and Technology Policy. The main objective of this process was to develop a range of SCC values using a defensible set of input assumptions that are grounded in the existing literature. In this way, key uncertainties and model differences can more transparently and consistently inform the range of SCC estimates used in the rulemaking process.

The interagency group selected four SCC estimates for use in regulatory analyses. For 2010, these estimates are \$5, \$21, \$35, and \$65 (in 2007 dollars). The first three estimates are based on the average SCC across models and socio-economic and emissions scenarios at the 5, 3, and 2.5 percent discount rates, respectively. The fourth value is included to represent the higher-than-expected impacts from temperature change further out in the tails of the SCC distribution. For this purpose, we use the SCC value for the 95^{th} percentile at a 3 percent discount rate. The central value is the average SCC across models at the 3 percent discount rate. For purposes of capturing the uncertainties involved in regulatory impact analysis, we emphasize the importance and value of considering the full range. These SCC estimates also grow over time. For instance, the central value increases to \$24 per ton of CO_2 in 2015 and \$26 per ton of CO_2 in 2020. See Appendix A for the full range of annual SCC estimates from 2010 to 2050.

It is important to emphasize that the interagency process is committed to updating these estimates as the science and economic understanding of climate change and its impacts on society improves over time. Specifically, we have set a preliminary goal of revisiting the SCC values within two years or at such time as substantially updated models become available, and to continue to support research in this area. In the meantime, we will continue to explore the issues raised in this document and consider public comments as part of the ongoing interagency process.

II. Social Cost of Carbon Values Used in Past Regulatory Analyses

To date, economic analyses for Federal regulations have used a wide range of values to estimate the benefits associated with reducing carbon dioxide emissions. In the final model year 2011 CAFE rule, the Department of Transportation (DOT) used both a "domestic" SCC value of \$2 per ton of CO_2 and a "global" SCC value of \$33 per ton of CO_2 for 2007 emission reductions (in 2007 dollars), increasing both values at 2.4 percent per year. It also included a sensitivity analysis at \$80 per ton of CO_2. A domestic SCC value is meant to reflect the value of damages in the United States resulting from a unit change in carbon dioxide emissions, while a global SCC value is meant to reflect the value of damages worldwide.

A 2008 regulation proposed by DOT assumed a domestic SCC value of \$7 per ton CO_2 (in 2006 dollars) for 2011 emission reductions (with a range of \$0-\$14 for sensitivity analysis), also increasing at 2.4 percent per year. A regulation finalized by DOE in October of 2008 used a domestic SCC range of \$0 to \$20 per ton CO_2 for 2007 emission reductions (in 2007 dollars). In addition, EPA's 2008 Advance Notice of Proposed Rulemaking for Greenhouse Gases identified what it described as "very preliminary" SCC estimates subject to revision. EPA's global mean values were \$68 and \$40 per ton CO_2 for discount rates of approximately 2 percent and 3 percent, respectively (in 2006 dollars for 2007 emissions).

In 2009, an interagency process was initiated to offer a preliminary assessment of how best to quantify the benefits from reducing carbon dioxide emissions. To ensure consistency in how benefits are evaluated across agencies, the Administration sought to develop a transparent and defensible method, specifically designed for the rulemaking process, to quantify avoided climate change damages from reduced CO_2 emissions. The interagency group did not undertake any original analysis. Instead, it combined SCC estimates from the existing literature to use as interim values until a more comprehensive analysis could be conducted.

The outcome of the preliminary assessment by the interagency group was a set of five interim values: global SCC estimates for 2007 (in 2006 dollars) of \$55, \$33, \$19, \$10, and \$5 per ton of CO_2. The \$33 and \$5 values represented model-weighted means of the published estimates produced from the most recently available versions of three integrated assessment models—DICE, PAGE, and FUND—at approximately 3 and 5 percent discount rates. The \$55 and \$10 values were derived by adjusting the published estimates for uncertainty in the discount rate (using factors developed by Newell and Pizer (2003)) at 3 and 5 percent discount rates, respectively. The \$19 value was chosen as a central value between the \$5 and \$33 per ton estimates. All of these values were assumed to increase at 3 percent annually to represent growth in incremental damages over time as the magnitude of climate change increases.

These interim values represent the first sustained interagency effort within the U.S. government to develop an SCC for use in regulatory analysis. The results of this preliminary effort were presented in several proposed and final rules and were offered for public comment in connection with proposed rules, including the joint EPA-DOT fuel economy and CO_2 tailpipe emission proposed rules.

III. Approach and Key Assumptions

Since the release of the interim values, interagency group has reconvened on a regular basis to generate improved SCC estimates. Specifically, the group has considered public comments and further explored the technical literature in relevant fields. This section details the several choices and assumptions that underlie the resulting estimates of the SCC.

It is important to recognize that a number of key uncertainties remain, and that current SCC estimates should be treated as provisional and revisable since they will evolve with improved scientific and economic understanding. The interagency group also recognizes that the existing models are imperfect and incomplete. The National Academy of Science (2009) points out that there is tension between the goal of producing quantified estimates of the economic damages from an incremental ton of carbon and the limits of existing efforts to model these effects. Throughout this document, we highlight a number of concerns and problems that should be addressed by the research community, including research programs housed in many of the agencies participating in the interagency process to estimate the SCC.

The U.S. Government will periodically review and reconsider estimates of the SCC used for cost-benefit analyses to reflect increasing knowledge of the science and economics of climate impacts, as well as improvements in modeling. In this context, statements recognizing the limitations of the analysis and calling for further research take on exceptional significance. The interagency group offers the new SCC values with all due humility about the uncertainties embedded in them and with a sincere promise to continue work to improve them.

A. Integrated Assessment Models

We rely on three integrated assessment models (IAMs) commonly used to estimate the SCC: the FUND, DICE, and PAGE models.[2] These models are frequently cited in the peer-reviewed literature and used in the IPCC assessment. Each model is given equal weight in the SCC values developed through this process, bearing in mind their different limitations (discussed below).

These models are useful because they combine climate processes, economic growth, and feedbacks between the climate and the global economy into a single modeling framework. At the same time, they gain this advantage at the expense of a more detailed representation of the underlying climatic and economic systems. DICE, PAGE, and FUND all take stylized, reduced-form approaches (see NRC 2009 for a more detailed discussion; see Nordhaus 2008 on the possible advantages of this approach). Other IAMs may better reflect the complexity of the science in their modeling frameworks but do not link physical impacts to economic damages. There is currently a limited amount of research linking climate impacts to economic damages, which makes this exercise even more difficult. Underlying the three IAMs selected for this exercise are a number of simplifying assumptions and judgments reflecting the various modelers' best attempts to synthesize the available scientific and economic research characterizing these relationships.

The three IAMs translate emissions into changes in atmospheric greenhouse concentrations, atmospheric concentrations into changes in temperature, and changes in temperature into economic damages. The emissions projections used in the models are based on specified socio-economic (GDP and population) pathways. These emissions are translated into concentrations using the carbon cycle built into each model, and concentrations are translated into warming based on each model's simplified representation of the climate and a key parameter, climate sensitivity. Each model uses a different approach to translate warming into damages. Finally, transforming the stream of economic damages over time into a single value requires judgments about how to discount them.

Each model takes a slightly different approach to model how changes in emissions result in changes in economic damages. In PAGE, for example, the consumption-equivalent damages in each period are calculated as a fraction of GDP, depending on the temperature in that period relative to the pre-industrial average temperature in each region. In FUND, damages in each period also depend on the rate of temperature change from the prior period. In DICE, temperature affects both consumption and investment. We describe each model in greater detail here. In a later section, we discuss key gaps in how the models account for various scientific and economic processes (e.g. the probability of catastrophe, and the ability to adapt to climate change and the physical changes it causes).

[2] The DICE (Dynamic Integrated Climate and Economy) model by William Nordhaus evolved from a series of energy models and was first presented in 1990 (Nordhaus and Boyer 2000, Nordhaus 2008). The PAGE (Policy Analysis of the Greenhouse Effect) model was developed by Chris Hope in 1991 for use by European decision-makers in assessing the marginal impact of carbon emissions (Hope 2006, Hope 2008). The FUND (Climate Framework for Uncertainty, Negotiation, and Distribution) model, developed by Richard Tol in the early 1990s, originally to study international capital transfers in climate policy. is now widely used to study climate impacts (e.g., Tol 2002a, Tol 2002b, Anthoff et al. 2009, Tol 2009).

The parameters and assumptions embedded in the three models vary widely. A key objective of the interagency process was to enable a consistent exploration of the three models while respecting the different approaches to quantifying damages taken by the key modelers in the field. An extensive review of the literature was conducted to select three sets of input parameters for these models: climate sensitivity, socio-economic and emissions trajectories, and discount rates. A probability distribution for climate sensitivity was specified as an input into all three models. In addition, the interagency group used a range of scenarios for the socio-economic parameters and a range of values for the discount rate. All other model features were left unchanged, relying on the model developers' best estimates and judgments. In DICE, these parameters are handled deterministically and represented by fixed constants; in PAGE, most parameters are represented by probability distributions. FUND was also run in a mode in which parameters were treated probabilistically.

The sensitivity of the results to other aspects of the models (e.g. the carbon cycle or damage function) is also important to explore in the context of future revisions to the SCC but has not been incorporated into these estimates. Areas for future research are highlighted at the end of this document.

The DICE Model

The DICE model is an optimal growth model based on a global production function with an extra stock variable (atmospheric carbon dioxide concentrations). Emission reductions are treated as analogous to investment in "natural capital." By investing in natural capital today through reductions in emissions—implying reduced consumption—harmful effects of climate change can be avoided and future consumption thereby increased.

For purposes of estimating the SCC, carbon dioxide emissions are a function of global GDP and the carbon intensity of economic output, with the latter declining over time due to technological progress. The DICE damage function links global average temperature to the overall impact on the world economy. It varies quadratically with temperature change to capture the more rapid increase in damages expected to occur under more extreme climate change, and is calibrated to include the effects of warming on the production of market and nonmarket goods and services. It incorporates impacts on agriculture, coastal areas (due to sea level rise), "other vulnerable market sectors" (based primarily on changes in energy use), human health (based on climate-related diseases, such as malaria and dengue fever, and pollution), non-market amenities (based on outdoor recreation), and human settlements and ecosystems. The DICE damage function also includes the expected value of damages associated with low probability, high impact "catastrophic" climate change. This last component is calibrated based on a survey of experts (Nordhaus 1994). The expected value of these impacts is then added to the other market and non-market impacts mentioned above.

No structural components of the DICE model represent adaptation explicitly, though it is included implicitly through the choice of studies used to calibrate the aggregate damage function. For example, its agricultural impact estimates assume that farmers can adjust land use decisions in response to changing climate conditions, and its health impact estimates assume improvements in healthcare over time. In addition, the small impacts on forestry, water systems, construction, fisheries, and outdoor recreation imply optimistic and costless adaptation in these sectors (Nordhaus and Boyer, 2000; Warren et al., 2006). Costs of resettlement due to sea level rise are incorporated into damage estimates, but their magnitude is not clearly reported. Mastrandrea's (2009) review concludes that "in general, DICE assumes very effective adaptation, and largely ignores adaptation costs."

Note that the damage function in DICE has a somewhat different meaning from the damage functions in FUND and PAGE. Because GDP is endogenous in DICE and because damages in a given year reduce investment in that year, damages propagate forward in time and reduce GDP in future years. In contrast, GDP is exogenous in FUND and PAGE, so damages in any given year do not propagate forward.[3]

The PAGE Model

PAGE2002 (version 1.4epm) treats GDP growth as exogenous. It divides impacts into economic, non-economic, and catastrophic categories and calculates these impacts separately for eight geographic regions. Damages in each region are expressed as a fraction of output, where the fraction lost depends on the temperature change in each region. Damages are expressed as power functions of temperature change. The exponents of the damage function are the same in all regions but are treated as uncertain, with values ranging from 1 to 3 (instead of being fixed at 2 as in DICE).

PAGE2002 includes the consequences of catastrophic events in a separate damage sub-function. Unlike DICE, PAGE2002 models these events probabilistically. The probability of a "discontinuity" (i.e., a catastrophic event) is assumed to increase with temperature above a specified threshold. The threshold temperature, the rate at which the probability of experiencing a discontinuity increases above the threshold, and the magnitude of the resulting catastrophe are all modeled probabilistically.

Adaptation is explicitly included in PAGE. Impacts are assumed to occur for temperature increases above some tolerable level (2°C for developed countries and 0°C for developing countries for economic impacts, and 0°C for all regions for non-economic impacts), but adaptation is assumed to reduce these impacts. Default values in PAGE2002 assume that the developed countries can ultimately eliminate up to 90 percent of all economic impacts beyond the tolerable 2°C increase and that developing countries can eventually eliminate 50 percent of their economic impacts. All regions are assumed to be able to mitigate 25 percent of the non-economic impacts through adaptation (Hope 2006).

The FUND Model

Like PAGE, the FUND model treats GDP growth as exogenous. It includes separately calibrated damage functions for eight market and nonmarket sectors: agriculture, forestry, water, energy (based on heating and cooling demand), sea level rise (based on the value of land lost and the cost of protection),

[3] Using the default assumptions in DICE 2007, this effect generates an approximately 25 percent increase in the SCC relative to damages calculated by fixing GDP. In DICE2007, the time path of GDP is endogenous. Specifically, the path of GDP depends on the rate of saving and level of abatement in each period chosen by the optimizing representative agent in the model. We made two modifications to DICE to make it consistent with EMF GDP trajectories (see next section): we assumed a fixed rate of savings of 20%, and we re-calibrated the exogenous path of total factor productivity so that DICE would produce GDP projections in the absence of warming that exactly matched the EMF scenarios.

ecosystems, human health (diarrhea, vector-borne diseases, and cardiovascular and respiratory mortality), and extreme weather. Each impact sector has a different functional form, and is calculated separately for sixteen geographic regions. In some impact sectors, the fraction of output lost or gained due to climate change depends not only on the absolute temperature change but also on the rate of temperature change and level of regional income.[4] In the forestry and agricultural sectors, economic damages also depend on CO_2 concentrations.

Tol (2009) discusses impacts not included in FUND, noting that many are likely to have a relatively small effect on damage estimates (both positive and negative). However, he characterizes several omitted impacts as “big unknowns”: for instance, extreme climate scenarios, biodiversity loss, and effects on economic development and political violence. With regard to potentially catastrophic events, he notes, “Exactly what would cause these sorts of changes or what effects they would have are not well-understood, although the chance of any one of them happening seems low. But they do have the potential to happen relatively quickly, and if they did, the costs could be substantial. Only a few studies of climate change have examined these issues.”

Adaptation is included both implicitly and explicitly in FUND. Explicit adaptation is seen in the agriculture and sea level rise sectors. Implicit adaptation is included in sectors such as energy and human health, where wealthier populations are assumed to be less vulnerable to climate impacts. For example, the damages to agriculture are the sum of three effects: (1) those due to the rate of temperature change (damages are always positive); (2) those due to the level of temperature change (damages can be positive or negative depending on region and temperature); and (3) those from CO_2 fertilization (damages are generally negative but diminishing to zero).

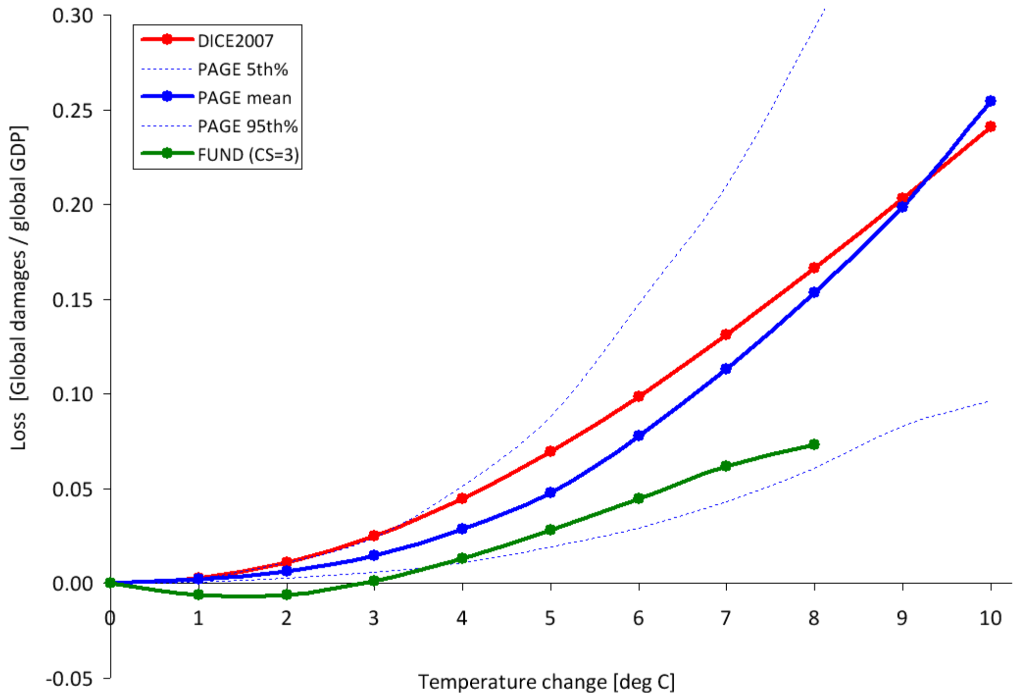
Adaptation is incorporated into FUND by allowing damages to be smaller if climate change happens more slowly. The combined effect of CO_2 fertilization in the agricultural sector, positive impacts to some regions from higher temperatures, and sufficiently slow increases in temperature across these sectors can result in negative economic damages from climate change.

Damage Functions

To generate revised SCC values, we rely on the IAM modelers’ current best judgments of how to represent the effects of climate change (represented by the increase in global-average surface temperature) on the consumption-equivalent value of both market and non-market goods (represented as a fraction of global GDP). We recognize that these representations are incomplete and highly uncertain. But given the paucity of data linking the physical impacts to economic damages, we were not able to identify a better way to translate changes in climate into net economic damages, short of launching our own research program.

[4] In the deterministic version of FUND, the majority of damages are attributable to increased air conditioning demand, while reduced cold stress in Europe, North America, and Central and East Asia results in health benefits in those regions at low to moderate levels of warming (Warren et al., 2006).

Figure 1A: Annual Consumption Loss as a Fraction of Global GDP in 2100 Due to an Increase in Annual - Global Temperature in the DICE, FUND, and PAGE models[5]



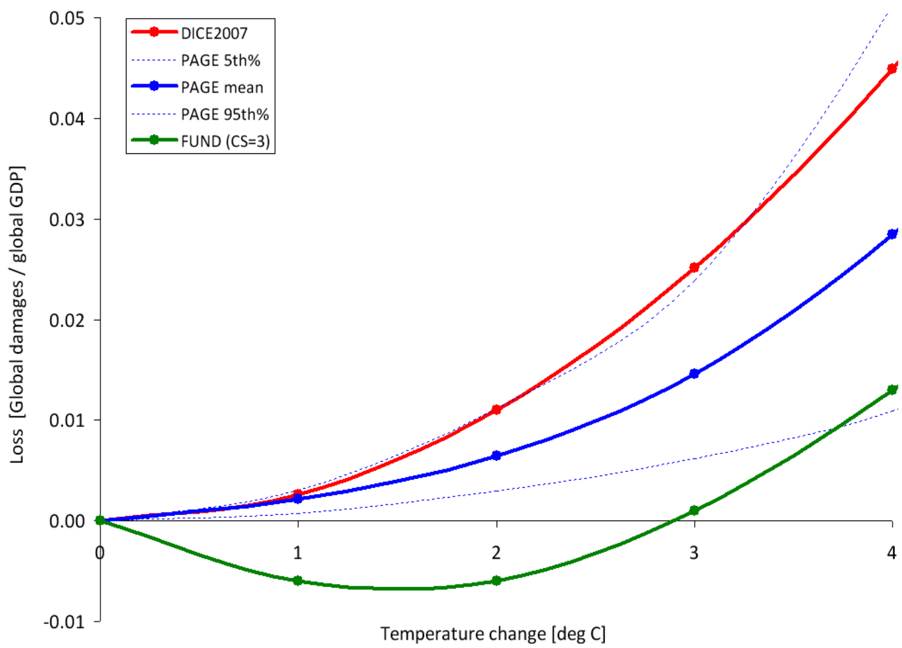
The damage functions for the three IAMs are presented in Figures 1A and 1B, using the modeler's default scenarios and mean input assumptions. There are significant differences between the three models both at lower (figure 1B) and higher (figure 1A) increases in global-average temperature.

The lack of agreement among the models at lower temperature increases is underscored by the fact that the damages from FUND are well below the 5th percentile estimated by PAGE, while the damages estimated by DICE are roughly equal to the 95th percentile estimated by PAGE. This is significant because at higher discount rates we expect that a greater proportion of the SCC value is due to damages in years with lower temperature increases. For example, when the discount rate is 2.5 percent, about 45 percent of the 2010 SCC value in DICE is due to damages that occur in years when the temperature is less than or equal to 3 °C. This increases to approximately 55 percent and 80 percent at discount rates of 3 and 5 percent, respectively.

These differences underscore the need for a thorough review of damage functions—in particular, how the models incorporate adaptation, technological change, and catastrophic damages. Gaps in the literature make modifying these aspects of the models challenging, which highlights the need for additional research. As knowledge improves, the Federal government is committed to exploring how these (and other) models can be modified to incorporate more accurate estimates of damages.

[5] The x-axis represents increases in annual, rather than equilibrium, temperature, while the y-axis represents the annual stream of benefits as a share of global GDP. Each specific combination of climate sensitivity, socio-economic, and emissions parameters will produce a different realization of damages for each IAM. The damage functions represented in Figures 1A and 1B are the outcome of default assumptions. For instance, under alternate assumptions, the damages from FUND may cross from negative to positive at less than or greater than 3 °C.

Figure 1B: Annual Consumption Loss for Lower Temperature Changes in DICE, FUND, and PAGE -



B. Global versus Domestic Measures of SCC

Because of the distinctive nature of the climate change problem, we center our current attention on a global measure of SCC. This approach is the same as that taken for the interim values, but it otherwise represents a departure from past practices, which tended to put greater emphasis on a domestic measure of SCC (limited to impacts of climate change experienced within U.S. borders). As a matter of law, consideration of both global and domestic values is generally permissible; the relevant statutory provisions are usually ambiguous and allow selection of either measure.[6]

Global SCC

Under current OMB guidance contained in Circular A-4, analysis of economically significant proposed and final regulations from the domestic perspective is required, while analysis from the international perspective is optional. However, the climate change problem is highly unusual in at least two respects. First, it involves a global externality: emissions of most greenhouse gases contribute to damages around the world even when they are emitted in the United States. Consequently, to address the global nature of the problem, the SCC must incorporate the full (global) damages caused by GHG emissions. Second, climate change presents a problem that the United States alone cannot solve. Even if the United States were to reduce its greenhouse gas emissions to zero, that step would be far from enough to avoid substantial climate change. Other countries would also need to take action to reduce emissions if

[6] It is true that federal statutes are presumed not to have extraterritorial effect, in part to ensure that the laws of the United States respect the interests of foreign sovereigns. But use of a global measure for the SCC does not give extraterritorial effect to federal law and hence does not intrude on such interests.

significant changes in the global climate are to be avoided. Emphasizing the need for a global solution to a global problem, the United States has been actively involved in seeking international agreements to reduce emissions and in encouraging other nations, including emerging major economies, to take significant steps to reduce emissions. When these considerations are taken as a whole, the interagency group concluded that a global measure of the benefits from reducing U.S. emissions is preferable.

When quantifying the damages associated with a change in emissions, a number of analysts (e.g., Anthoff, et al. 2009a) employ "equity weighting" to aggregate changes in consumption across regions. This weighting takes into account the relative reductions in wealth in different regions of the world. A per-capita loss of $500 in GDP, for instance, is weighted more heavily in a country with a per-capita GDP of $2,000 than in one with a per-capita GDP of $40,000. The main argument for this approach is that a loss of $500 in a poor country causes a greater reduction in utility or welfare than does the same loss in a wealthy nation. Notwithstanding the theoretical claims on behalf of equity weighting, the interagency group concluded that this approach would not be appropriate for estimating a SCC value used in domestic regulatory analysis.[7] For this reason, the group concluded that using the global (rather than domestic) value, without equity weighting, is the appropriate approach.

Domestic SCC

As an empirical matter, the development of a domestic SCC is greatly complicated by the relatively few region- or country-specific estimates of the SCC in the literature. One potential source of estimates comes from the FUND model. The resulting estimates suggest that the ratio of domestic to global benefits of emission reductions varies with key parameter assumptions. For example, with a 2.5 or 3 percent discount rate, the U.S. benefit is about 7-10 percent of the global benefit, on average, across the scenarios analyzed. Alternatively, if the fraction of GDP lost due to climate change is assumed to be similar across countries, the domestic benefit would be proportional to the U.S. share of global GDP, which is currently about 23 percent.[8]

On the basis of this evidence, the interagency workgroup determined that a range of values from 7 to 23 percent should be used to adjust the global SCC to calculate domestic effects. Reported domestic values should use this range. It is recognized that these values are approximate, provisional, and highly speculative. There is no a priori reason why domestic benefits should be a constant fraction of net global damages over time. Further, FUND does not account for how damages in other regions could affect the United States (e.g., global migration, economic and political destabilization). If more accurate methods for calculating the domestic SCC become available, the Federal government will examine these to determine whether to update its approach.

[7] It is plausible that a loss of $X inflicts more serious harm on a poor nation than on a wealthy one, but development of the appropriate "equity weight" is challenging. Emissions reductions also impose costs, and hence a full account would have to consider that a given cost of emissions reductions imposes a greater utility or welfare loss on a poor nation than on a wealthy one. Even if equity weighting—for both the costs and benefits of emissions reductions—is appropriate when considering the utility or welfare effects of international action, the interagency group concluded that it should not be used in developing an SCC for use in regulatory policy at this time.

[8] Based on 2008 GDP (in current US dollars) from the *World Bank Development Indicators Report*.

C. Valuing Non-CO_2 Emissions

While CO_2 is the most prevalent greenhouse gas emitted into the atmosphere, the U.S. included five other greenhouse gases in its recent endangerment finding: methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride. The climate impact of these gases is commonly discussed in terms of their 100-year global warming potential (GWP). GWP measures the ability of different gases to trap heat in the atmosphere (i.e., radiative forcing per unit of mass) over a particular timeframe relative to CO_2. However, because these gases differ in both radiative forcing and atmospheric lifetimes, their relative damages are not constant over time. For example, because methane has a short lifetime, its impacts occur primarily in the near term and thus are not discounted as heavily as those caused by longer-lived gases. Impacts other than temperature change also vary across gases in ways that are not captured by GWP. For instance, CO_2 emissions, unlike methane and other greenhouse gases, contribute to ocean acidification. Likewise, damages from methane emissions are not offset by the positive effect of CO_2 fertilization. Thus, transforming gases into CO_2-equivalents using GWP, and then multiplying the carbon-equivalents by the SCC, would not result in accurate estimates of the social costs of non-CO_2 gases.

In light of these limitations, and the significant contributions of non-CO_2 emissions to climate change, further research is required to link non-CO_2 emissions to economic impacts. Such work would feed into efforts to develop a monetized value of reductions in non-CO_2 greenhouse gas emissions. As part of ongoing work to further improve the SCC estimates, the interagency group hopes to develop methods to value these other greenhouse gases. The goal is to develop these estimates by the time we issue revised SCC estimates for carbon dioxide emissions.

D. Equilibrium Climate Sensitivity

Equilibrium climate sensitivity (ECS) is a key input parameter for the DICE, PAGE, and FUND models.[9] It is defined as the long-term increase in the annual global-average surface temperature from a doubling of atmospheric CO_2 concentration relative to pre-industrial levels (or stabilization at a concentration of approximately 550 parts per million (ppm)). Uncertainties in this important parameter have received substantial attention in the peer-reviewed literature.

The most authoritative statement about equilibrium climate sensitivity appears in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC):

> *Basing our assessment on a combination of several independent lines of evidence…including observed climate change and the strength of known feedbacks simulated in [global climate models], we conclude that the global mean equilibrium warming for doubling CO_2, or 'equilibrium climate*

[9] The equilibrium climate sensitivity includes the response of the climate system to increased greenhouse gas concentrations over the short to medium term (up to 100-200 years), but it does not include long-term feedback effects due to possible large-scale changes in ice sheets or the biosphere, which occur on a time scale of many hundreds to thousands of years (e.g. Hansen et al. 2007).

sensitivity', is likely to lie in the range 2 °C to 4.5 °C, with a most likely value of about 3 °C. Equilibrium climate sensitivity is very likely larger than 1.5 °C. [10]

For fundamental physical reasons as well as data limitations, values substantially higher than 4.5 °C still cannot be excluded, but agreement with observations and proxy data is generally worse for those high values than for values in the 2 °C to 4.5 °C range. (Meehl et al., 2007, p 799)

After consulting with several lead authors of this chapter of the IPCC report, the interagency workgroup selected four candidate probability distributions and calibrated them to be consistent with the above statement: Roe and Baker (2007), log-normal, gamma, and Weibull. Table 1 included below gives summary statistics for the four calibrated distributions.

Table 1: Summary Statistics for Four Calibrated Climate Sensitivity Distributions

	Roe & Baker	Log-normal	Gamma	Weibull
Pr(ECS < 1.5°C)	0.013	0.050	0.070	0.102
Pr(2°C < ECS < 4.5°C)	0.667	0.667	0.667	0.667
5th percentile	1.72	1.49	1.37	1.13
10th percentile	1.91	1.74	1.65	1.48
Mode	2.34	2.52	2.65	2.90
Median (50th percentile)	3.00	3.00	3.00	3.00
Mean	3.50	3.28	3.19	3.07
90th percentile	5.86	5.14	4.93	4.69
95th percentile	7.14	5.97	5.59	5.17

Each distribution was calibrated by applying three constraints from the IPCC:

(1) a median equal to 3°C, to reflect the judgment of "a most likely value of about 3 °C";[11]
(2) two-thirds probability that the equilibrium climate sensitivity lies between 2 and 4.5 °C; and
(3) zero probability that it is less than 0°C or greater than 10°C (see Hegerl et al. 2006, p. 721).

We selected the calibrated Roe and Baker distribution from the four candidates for two reasons. First, the Roe and Baker distribution is the only one of the four that is based on a theoretical understanding of the response of the climate system to increased greenhouse gas concentrations (Roe and Baker 2007,

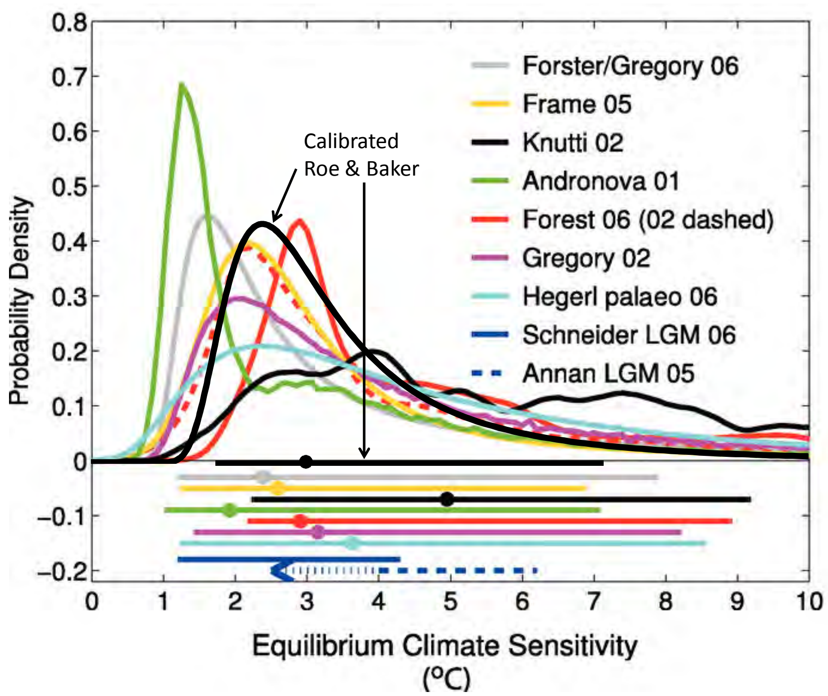
[10] This is in accord with the judgment that it "is likely to lie in the range 2 °C to 4.5 °C" and the IPCC definition of "likely" as greater than 66 percent probability (Le Treut et al.2007). "Very likely" indicates a greater than 90 percent probability.
[11] Strictly speaking, "most likely" refers to the mode of a distribution rather than the median, but common usage would allow the mode, median, or mean to serve as candidates for the central or "most likely" value and the IPCC report is not specific on this point. For the distributions we considered, the median was between the mode and the mean. For the Roe and Baker distribution, setting the median equal to 3°C, rather than the mode or mean, gave a 95th percentile that is more consistent with IPCC judgments and the literature. For example, setting the mean and mode equal to 3°C produced 95th percentiles of 5.6 and 8.6 °C, respectively, which are in the lower and upper end of the range in the literature. Finally, the median is closer to 3°C than is the mode for the truncated distributions selected by the IPCC (Hegerl, et al., 2006); the average median is 3.1 °C and the average mode is 2.3 °C, which is most consistent with a Roe and Baker distribution with the median set equal to 3 °C.

Roe 2008). In contrast, the other three distributions are mathematical functions that are arbitrarily chosen based on simplicity, convenience, and general shape. The Roe and Baker distribution results from three assumptions about climate response: (1) absent feedback effects, the equilibrium climate sensitivity is equal to 1.2 °C; (2) feedback factors are proportional to the change in surface temperature; and (3) uncertainties in feedback factors are normally distributed. There is widespread agreement on the first point and the second and third points are common assumptions.

Second, the calibrated Roe and Baker distribution better reflects the IPCC judgment that "values substantially higher than 4.5°C still cannot be excluded." Although the IPCC made no quantitative judgment, the 95th percentile of the calibrated Roe & Baker distribution (7.1 °C) is much closer to the mean and the median (7.2 °C) of the 95th percentiles of 21 previous studies summarized by Newbold and Daigneault (2009). It is also closer to the mean (7.5 °C) and median (7.9 °C) of the nine truncated distributions examined by the IPCC (Hegerl, et al., 2006) than are the 95th percentiles of the three other calibrated distributions (5.2-6.0 °C).

Finally, we note the IPCC judgment that the equilibrium climate sensitivity "is very likely larger than 1.5°C." Although the calibrated Roe & Baker distribution, for which the probability of equilibrium climate sensitivity being greater than 1.5°C is almost 99 percent, is not inconsistent with the IPCC definition of "very likely" as "greater than 90 percent probability," it reflects a greater degree of certainty about very low values of ECS than was expressed by the IPCC.

Figure 2: Estimates of the Probability Density Function for Equilibrium Climate Sensitivity (°C)



To show how the calibrated Roe and Baker distribution compares to different estimates of the probability distribution function of equilibrium climate sensitivity in the empirical literature, Figure 2 (below) overlays it on Figure 9.20 from the IPCC Fourth Assessment Report. These functions are scaled to integrate to unity between 0 °C and 10 °C. The horizontal bars show the respective 5 percent to 95 percent ranges; dots indicate the median estimate.[12]

E. Socio-Economic and Emissions Trajectories

Another key issue considered by the interagency group is how to select the set of socio-economic and emissions parameters for use in PAGE, DICE, and FUND. Socio-economic pathways are closely tied to climate damages because, all else equal, more and wealthier people tend to emit more greenhouse gases and also have a higher (absolute) willingness to pay to avoid climate disruptions. For this reason, we consider how to model several input parameters in tandem: GDP, population, CO_2 emissions, and non-CO_2 radiative forcing. A wide variety of scenarios have been developed and used for climate change policy simulations (e.g., SRES 2000, CCSP 2007, EMF 2009). In determining which scenarios are appropriate for inclusion, we aimed to select scenarios that span most of the plausible ranges of outcomes for these variables.

To accomplish this task in a transparent way, we decided to rely on the recent Stanford Energy Modeling Forum exercise, EMF-22. EMF-22 uses ten well-recognized models to evaluate substantial, coordinated global action to meet specific stabilization targets. A key advantage of relying on these data is that GDP, population, and emission trajectories are internally consistent for each model and scenario evaluated. The EMF-22 modeling effort also is preferable to the IPCC SRES due to their age (SRES were developed in 1997) and the fact that 3 of 4 of the SRES scenarios are now extreme outliers in one or more variables. Although the EMF-22 scenarios have not undergone the same level of scrutiny as the SRES scenarios, they are recent, peer-reviewed, published, and publicly available.

To estimate the SCC for use in evaluating domestic policies that will have a small effect on global cumulative emissions, we use socio-economic and emission trajectories that span a range of plausible scenarios. Five trajectories were selected from EMF-22 (see Table 2 below). Four of these represent potential business-as-usual (BAU) growth in population, wealth, and emissions and are associated with CO_2 (only) concentrations ranging from 612 to 889 ppm in 2100. One represents an emissions pathway that achieves stabilization at 550 ppm CO_2e (i.e., CO_2-only concentrations of 425 – 484 ppm or a radiative forcing of 3.7 W/m^2) in 2100, a lower-than-BAU trajectory.[13] Out of the 10 models included in the EMF-22 exercise, we selected the trajectories used by MiniCAM, MESSAGE, IMAGE, and the optimistic scenario from MERGE. For the BAU pathways, we used the GDP, population, and emission trajectories from each of these four models. For the 550 ppm CO_2e scenario, we averaged the GDP, population, and emission trajectories implied by these same four models.

[12] The estimates based on instrumental data are from Andronova and Schlesinger (2001), Forest et al. (2002; dashed line, anthropogenic forcings only), Forest et al. (2006; solid line, anthropogenic and natural forcings), Gregory et al. (2002a), Knutti et al. (2002), Frame et al. (2005), and Forster and Gregory (2006). Hegerl et al. (2006) are based on multiple palaeoclimatic reconstructions of north hemisphere mean temperatures over the last 700 years. Also shown are the 5-95 percent approximate ranges for two estimates from the last glacial maximum (dashed, Annan et al. 2005; solid, Schneider von Deimling et al. 2006), which are based on models with different structural properties.

[13] Such an emissions path would be consistent with widespread action by countries to mitigate GHG emissions, though it could also result from technological advances. It was chosen because it represents the most stringent case analyzed by the EMF-22 where all the models converge: a 550 ppm, not to exceed, full participation scenario.

Table 2: Socioeconomic and Emissions Projections from Select EMF-22 Reference Scenarios -

Reference Fossil and Industrial CO_2 Emissions ($GtCO_2$/yr) -

EMF – 22 Based Scenarios	2000	2010	2020	2030	2050	2100
IMAGE	26.6	31.9	36.9	40.0	45.3	60.1
MERGE Optimistic	24.6	31.5	37.6	45.1	66.5	117.9
MESSAGE	26.8	29.2	37.6	42.1	43.5	42.7
MiniCAM	26.5	31.8	38.0	45.1	57.8	80.5
550 ppm average	26.2	31.1	33.2	32.4	20.0	12.8

Reference GDP (using market exchange rates in trillion 2005$)[14]

EMF – 22 Based Scenarios	2000	2010	2020	2030	2050	2100
IMAGE	38.6	53.0	73.5	97.2	156.3	396.6
MERGE Optimistic	36.3	45.9	59.7	76.8	122.7	268.0
MESSAGE	38.1	52.3	69.4	91.4	153.7	334.9
MiniCAM	36.1	47.4	60.8	78.9	125.7	369.5
550 ppm average	37.1	49.6	65.6	85.5	137.4	337.9

Global Population (billions)

EMF – 22 Based Scenarios	2000	2010	2020	2030	2050	2100
IMAGE	6.1	6.9	7.6	8.2	9.0	9.1
MERGE Optimistic	6.0	6.8	7.5	8.2	9.0	9.7
MESSAGE	6.1	6.9	7.7	8.4	9.4	10.4
MiniCAM	6.0	6.8	7.5	8.1	8.8	8.7
550 ppm average	6.1	6.8	7.6	8.2	8.7	9.1

We explore how sensitive the SCC is to various assumptions about how the future will evolve without prejudging what is likely to occur. The interagency group considered formally assigning probability weights to different states of the world, but this proved challenging to do in an analytically rigorous way given the dearth of information on the likelihood of a full range of future socio-economic pathways.

There are a number of caveats. First, EMF BAU scenarios represent the modelers' judgment of the most likely pathway absent mitigation policies to reduce greenhouse gas emissions, rather than the wider range of possible outcomes. Nevertheless, these views of the most likely outcome span a wide range,

[14] While the EMF-22 models used market exchange rates (MER) to calculate global GDP, it is also possible to use purchasing power parity (PPP). PPP takes into account the different price levels across countries, so it more accurately describes relative standards of living across countries. MERs tend to make low-income countries appear poorer than they actually are. Because many models assume convergence in per capita income over time, use of MER-adjusted GDP gives rise to projections of higher economic growth in low income countries. There is an ongoing debate about how much this will affect estimated climate impacts. Critics of the use of MER argue that it leads to overstated economic growth and hence a significant upward bias in projections of greenhouse gas emissions, and unrealistically high future temperatures (e.g., Castles and Henderson 2003). Others argue that convergence of the emissions-intensity gap across countries at least partially offset the overstated income gap so that differences in exchange rates have less of an effect on emissions (Holtsmark and Alfsen, 2005; Tol, 2006). Nordhaus (2007b) argues that the ideal approach is to use superlative PPP accounts (i.e., using cross-sectional PPP measures for relative incomes and outputs and national accounts price and quantity indexes for time-series extrapolations). However, he notes that it important to keep this debate in perspective; it is by no means clear that exchange-rate-conversion issues are as important as uncertainties about population, technological change, or the many geophysical uncertainties.

from the more optimistic (e.g. abundant low-cost, low-carbon energy) to more pessimistic (e.g. constraints on the availability of nuclear and renewables).[15] Second, the socio-economic trajectories associated with a 550 ppm CO_2e concentration scenario are not derived from an assessment of what policy is optimal from a benefit-cost standpoint. Rather, it is indicative of one possible future outcome. The emission trajectories underlying some BAU scenarios (e.g. MESSAGE's 612 ppm) also are consistent with some modest policy action to address climate change.[16] We chose not to include socio-economic trajectories that achieve even lower GHG concentrations at this time, given the difficulty many models had in converging to meet these targets.

For comparison purposes, the Energy Information Agency in its 2009 Annual Energy Outlook projected that global carbon dioxide emissions will grow to 30.8, 35.6, and 40.4 gigatons in 2010, 2020, and 2030, respectively, while world GDP is projected to be $51.8, $71.0 and $93.9 trillion (in 2005 dollars using market exchange rates) in 2010, 2020, and 2030, respectively. These projections are consistent with one or more EMF-22 scenarios. Likewise, the United Nations' 2008 Population Prospect projects population will grow from 6.1 billion people in 2000 to 9.1 billion people in 2050, which is close to the population trajectories for the IMAGE, MiniCAM, and MERGE models.

In addition to fossil and industrial CO_2 emissions, each EMF scenario provides projections of methane, nitrous oxide, fluorinated greenhouse gases, and net land use CO_2 emissions out to 2100. These assumptions also are used in the three models while retaining the default radiative forcings due to other factors (e.g. aerosols and other gases). See the Appendix for greater detail.

F. Discount Rate

The choice of a discount rate, especially over long periods of time, raises highly contested and exceedingly difficult questions of science, economics, philosophy, and law. Although it is well understood that the discount rate has a large influence on the current value of future damages, there is no consensus about what rates to use in this context. Because carbon dioxide emissions are long-lived, subsequent damages occur over many years. In calculating the SCC, we first estimate the future damages to agriculture, human health, and other market and non-market sectors from an additional unit of carbon dioxide emitted in a particular year in terms of reduced consumption (or consumption equivalents) due to the impacts of elevated temperatures, as represented in each of the three IAMs. Then we discount the stream of future damages to its present value in the year when the additional unit of emissions was released using the selected discount rate, which is intended to reflect society's marginal rate of substitution between consumption in different time periods.

For rules with both intra- and intergenerational effects, agencies traditionally employ constant discount rates of both 3 percent and 7 percent in accordance with OMB Circular A-4. As Circular A-4 acknowledges, however, the choice of discount rate for intergenerational problems raises distinctive

[15] For instance, in the MESSAGE model's reference case total primary energy production from nuclear, biomass, and non-biomass renewables is projected to increase from about 15 percent of total primary energy in 2000 to 54 percent in 2100. In comparison, the MiniCAM reference case shows 10 percent in 2000 and 21 percent in 2100.

[16] For example, MiniCAM projects if all non-US OECD countries reduce CO_2 emissions to 83 percent below 2005 levels by 2050 (per the G-8 agreement) but all other countries continue along a BAU path CO_2 concentrations in 2100 would drop from 794 ppmv in its reference case to 762 ppmv.

problems and presents considerable challenges. After reviewing those challenges, Circular A-4 states, "If your rule will have important intergenerational benefits or costs you might consider a further sensitivity analysis using a lower but positive discount rate in addition to calculating net benefits using discount rates of 3 and 7 percent." For the specific purpose of developing the SCC, we adapt and revise that approach here.

Arrow et al. (1996) outlined two main approaches to determine the discount rate for climate change analysis, which they labeled "descriptive" and "prescriptive." The descriptive approach reflects a positive (non-normative) perspective based on observations of people's actual choices—e.g., savings versus consumption decisions over time, and allocations of savings among more and less risky investments. Advocates of this approach generally call for inferring the discount rate from market rates of return "because of a lack of justification for choosing a social welfare function that is any different than what decision makers [individuals] actually use" (Arrow et al. 1996).

One theoretical foundation for the cost-benefit analyses in which the social cost of carbon will be used—the Kaldor-Hicks potential-compensation test—also suggests that market rates should be used to discount future benefits and costs, because it is the market interest rate that would govern the returns potentially set aside today to compensate future individuals for climate damages that they bear (e.g., Just et al. 2004). As some have noted, the word "potentially" is an important qualification; there is no assurance that such returns will actually be set aside to provide compensation, and the very idea of compensation is difficult to define in the intergenerational context. On the other hand, societies provide compensation to future generations through investments in human capital and the resulting increase in knowledge, as well as infrastructure and other physical capital.

The prescriptive approach specifies a social welfare function that formalizes the normative judgments that the decision-maker wants explicitly to incorporate into the policy evaluation—e.g., how inter-personal comparisons of utility should be made, and how the welfare of future generations should be weighed against that of the present generation. Ramsey (1928), for example, has argued that it is "ethically indefensible" to apply a positive pure rate of time preference to discount values across generations, and many agree with this view.

Other concerns also motivate making adjustments to descriptive discount rates. In particular, it has been noted that the preferences of future generations with regard to consumption versus environmental amenities may not be the same as those today, making the current market rate on consumption an inappropriate metric by which to discount future climate-related damages. Others argue that the discount rate should be below market rates to correct for market distortions and uncertainties or inefficiencies in intergenerational transfers of wealth, which in the Kaldor-Hicks logic are presumed to compensate future generations for damage (a potentially controversial assumption, as noted above) (Arrow et al. 1996, Weitzman 1999).

Further, a legitimate concern about both descriptive and prescriptive approaches is that they tend to obscure important heterogeneity in the population. The utility function that underlies the prescriptive approach assumes a representative agent with perfect foresight and no credit constraints. This is an artificial rendering of the real world that misses many of the frictions that characterize individuals' lives and indeed the available descriptive evidence supports this. For instance, many individuals smooth consumption by borrowing with credit cards that have relatively high rates. Some are unable to access traditional credit markets and rely on payday lending operations or other high cost forms of smoothing consumption. Whether one puts greater weight on the prescriptive or descriptive approach, the high interest rates that credit-constrained individuals accept suggest that some account should be given to the discount rates revealed by their behavior.

We draw on both approaches but rely primarily on the descriptive approach to inform the choice of discount rate. With recognition of its limitations, we find this approach to be the most defensible and transparent given its consistency with the standard contemporary theoretical foundations of benefit-cost analysis and with the approach required by OMB's existing guidance. The logic of this framework also suggests that market rates should be used for discounting future consumption-equivalent damages. Regardless of the theoretical approach used to derive the appropriate discount rate(s), we note the inherent conceptual and practical difficulties of adequately capturing consumption trade-offs over many decades or even centuries. While relying primarily on the descriptive approach in selecting specific discount rates, the interagency group has been keenly aware of the deeply normative dimensions of both the debate over discounting in the intergenerational context and the consequences of selecting one discount rate over another.

Historically Observed Interest Rates

In a market with no distortions, the return to savings would equal the private return on investment, and the market rate of interest would be the appropriate choice for the social discount rate. In the real world risk, taxes, and other market imperfections drive a wedge between the risk-free rate of return on capital and the consumption rate of interest. Thus, the literature recognizes two conceptual discount concepts—the consumption rate of interest and the opportunity cost of capital.

According to OMB's Circular A-4, it is appropriate to use the rate of return on capital when a regulation is expected to displace or alter the use of capital in the private sector. In this case, OMB recommends Agencies use a discount rate of 7 percent. When regulation is expected to primarily affect private consumption—for instance, via higher prices for goods and services—a lower discount rate of 3 percent is appropriate to reflect how private individuals trade-off current and future consumption.

The interagency group examined the economics literature and concluded that the consumption rate of interest is the correct concept to use in evaluating the benefits and costs of a marginal change in carbon emissions (see Lind 1990, Arrow et al 1996, and Arrow 2000). The consumption rate of interest also is appropriate when the impacts of a regulation are measured in consumption (-equivalent) units, as is done in the three integrated assessment models used for estimating the SCC.

Individuals use a variety of savings instruments that vary with risk level, time horizon, and tax characteristics. The standard analytic framework used to develop intuition about the discount rate typically assumes a representative agent with perfect foresight and no credit constraints. The risk-free rate is appropriate for discounting certain future benefits or costs, but the benefits calculated by IAMs are uncertain. To use the risk-free rate to discount uncertain benefits, these benefits first must be transformed into "certainty equivalents," that is the maximum certain amount that we would exchange for the uncertain amount. However, the calculation of the certainty-equivalent requires first estimating the correlation between the benefits of the policy and baseline consumption.

If the IAM projections of future impacts represent expected values (not certainty-equivalent values), then the appropriate discount rate generally does not equal the risk-free rate. If the benefits of the policy tend to be high in those states of the world in which consumption is low, then the certainty-equivalent benefits will be higher than the expected benefits (and vice versa). Since many (though not necessarily all) of the important impacts of climate change will flow through market sectors such as agriculture and energy, and since willingness to pay for environmental protections typically increases with income, we might expect a positive (though not necessarily perfect) correlation between the net benefits from climate policies and market returns. This line of reasoning suggests that the proper discount rate would exceed the riskless rate. Alternatively, a negative correlation between the returns to climate policies and market returns would imply that a discount rate below the riskless rate is appropriate.

This discussion suggests that both the post-tax riskless and risky rates can be used to capture individuals' consumption-equivalent interest rate. As a measure of the post-tax riskless rate, we calculate the average real return from Treasury notes over the longest time period available (those from Newell and Pizer 2003) and adjust for Federal taxes (the average marginal rate from tax years 2003 through 2006 is around 27 percent).[17] This calculation produces a real interest rate of about 2.7 percent, which is roughly consistent with Circular A-4's recommendation to use 3 percent to represent the consumption rate of interest.[18] A measure of the post-tax risky rate for investments whose returns are positively correlated with overall equity market returns can be obtained by adjusting pre-tax rates of household returns to risky investments (approximately 7 percent) for taxes yields a real rate of roughly 5 percent.[19]

The Ramsey Equation

Ramsey discounting also provides a useful framework to inform the choice of a discount rate. Under this approach, the analyst applies either positive or normative judgments in selecting values for the key parameters of the Ramsey equation: η (coefficient of relative risk aversion or elasticity of the marginal utility of consumption) and ρ (pure rate of time preference).[20] These are then combined with g (growth

[17] The literature argues for a risk-free rate on government bonds as an appropriate measure of the consumption rate of interest. Arrow (2000) suggests that it is roughly 3-4 percent. OMB cites evidence of a 3.1 percent pre-tax rate for 10-year Treasury notes in the A-4 guidance. Newell and Pizer (2003) find real interest rates between 3.5 and 4 percent for 30-year Treasury securities.

[18] The positive approach reflects how individuals make allocation choices across time, but it is important to keep in mind that we wish to reflect preferences for society as a whole, which generally has a longer planning horizon.

[19] Cambell et al (2001) estimates that the annual real return from stocks for 1900-1995 was about 7 percent. The annual real rate of return for the S&P 500 from 1950 – 2008 was about 6.8 percent. In the absence of a better way to population-weight the tax rates, we use the middle of the 20 – 40 percent range to derive a post-tax interest rate (Kotlikoff and Rapson 2006).

[20] The parameter ρ measures the *pure rate of time preference*: people's behavior reveals a preference for an increase in utility today versus the future. Consequently, it is standard to place a lower weight on utility in the future. The parameter η captures *diminishing marginal utility*: consumption in the future is likely to be higher than consumption today, so diminishing marginal utility of consumption implies that the same monetary damage will

rate of per-capita consumption) to equal the interest rate at which future monetized damages are discounted: $\rho + \eta \cdot g$.[21] In the simplest version of the Ramsey model, with an optimizing representative agent with perfect foresight, what we are calling the "Ramsey discount rate," $\rho + \eta \cdot g$, will be equal to the rate of return to capital, i.e., the market interest rate.

A review of the literature provides some guidance on reasonable parameter values for the Ramsey discounting equation, based on both prescriptive and descriptive approaches.

- η. Most papers in the climate change literature adopt values for η in the range of 0.5 to 3 (Weitzman cites plausible values as those ranging from 1 to 4), although not all authors articulate whether their choice is based on prescriptive or descriptive reasoning.[22] Dasgupta (2008) argues that η should be greater than 1 and may be as high as 3, since η equal to 1 suggests savings rates that do not conform to observed behavior.

- ρ. With respect to the pure rate of time preference, most papers in the climate change literature adopt values for ρ in the range of 0 to 3 percent per year. The very low rates tend to follow from moral judgments involving intergenerational neutrality. Some have argued that to use any value other than $\rho = 0$ would unjustly discriminate against future generations (e.g., Arrow et al. 1996, Stern et al. 2006). However, even in an inter-generational setting, it may make sense to use a small positive pure rate of time preference because of the small probability of unforeseen cataclysmic events (Stern et al. 2006).

- g. A commonly accepted approximation is around 2 percent per year. For the socio-economic scenarios used for this exercise, the EMF models assume that g is about 1.5-2 percent to 2100.

Some economists and non-economists have argued for constant discount rates below 2 percent based on the prescriptive approach. When grounded in the Ramsey framework, proponents of this approach have argued that a ρ of zero avoids giving preferential treatment to one generation over another. The choice of η has also been posed as an ethical choice linked to the value of an additional dollar in poorer

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cause a smaller reduction of utility for wealthier individuals, either in the future or in current generations. If $\eta = 0$, then a one dollar increase in income is equally valuable regardless of level of income; if $\eta = 1$, then a one percent increase in income is equally valuable no matter the level of income; and if $\eta > 1$, then a one percent increase in income is less valuable to wealthier individuals.

[21] In this case, g could be taken from the selected EMF socioeconomic scenarios or alternative assumptions about the rate of consumption growth.

[22] Empirical estimates of η span a wide range of values. A benchmark value of 2 is near the middle of the range of values estimated or used by Szpiro (1986), Hall and Jones (2007), Arrow (2007), Dasgupta (2006, 2008), Weitzman (2007, 2009), and Nordhaus (2008). However, Chetty (2006) developed a method of estimating η using data on labor supply behavior. He shows that existing evidence of the effects of wage changes on labor supply imposes a tight upper bound on the curvature of utility over wealth (CRRA < 2) with the mean implied value of 0.71 and concludes that the standard expected utility model cannot generate high levels of risk aversion without contradicting established facts about labor supply. Recent work has jointly estimated the components of the Ramsey equation. Evans and Sezer (2005) estimate $\eta = 1.49$ for 22 OECD countries. They also estimate $\rho = 1.08$ percent per year using data on mortality rates. Anthoff, et al. (2009b) estimate $\eta = 1.18$, and $\rho = 1.4$ percent. When they multiply the bivariate probability distributions from their work and Evans and Sezer (2005) together, they find $\eta = 1.47$, and $\rho = 1.07$.

countries compared to wealthier ones. Stern et al. (2006) applies this perspective through his choice of ρ = 0.1 percent per year, η = 1 and g = 1.3 percent per year, which yields an annual discount rate of 1.4 percent. In the context of permanent income savings behavior, however, Stern's assumptions suggest that individuals would save 93 percent of their income.[23]

Recently, Stern (2008) revisited the values used in Stern et al. (2006), stating that there is a case to be made for raising η due to the amount of weight lower values place on damages far in the future (over 90 percent of expected damages occur after 2200 with η = 1). Using Stern's assumption that ρ = 0.1 percent, combined with a η of 1.5 to 2 and his original growth rate, yields a discount rate greater 2 percent.

We conclude that arguments made under the prescriptive approach can be used to justify discount rates between roughly 1.4 and 3.1 percent. In light of concerns about the most appropriate value for η, we find it difficult to justify rates at the lower end of this range under the Ramsey framework.

Accounting for Uncertainty in the Discount Rate

While the consumption rate of interest is an important driver of the benefits estimate, it is uncertain over time. Ideally, we would formally model this uncertainty, just as we do for climate sensitivity. Weitzman (1998, 2001) showed theoretically and Newell and Pizer (2003) and Groom et al. (2006) confirm empirically that discount rate uncertainty can have a large effect on net present values. A main result from these studies is that if there is a persistent element to the uncertainty in the discount rate (e.g., the rate follows a random walk), then it will result in an effective (or certainty-equivalent) discount rate that declines over time. Consequently, lower discount rates tend to dominate over the very long term (see Weitzman 1998, 1999, 2001; Newell and Pizer 2003; Groom et al. 2006; Gollier 2008; Summers and Zeckhauser 2008; and Gollier and Weitzman 2009).

The proper way to model discount rate uncertainty remains an active area of research. Newell and Pizer (2003) employ a model of how long-term interest rates change over time to forecast future discount rates. Their model incorporates some of the basic features of how interest rates move over time, and its parameters are estimated based on historical observations of long-term rates. Subsequent work on this topic, most notably Groom et al. (2006), uses more general models of interest rate dynamics to allow for better forecasts. Specifically, the volatility of interest rates depends on whether rates are currently low or high and variation in the level of persistence over time.

While Newell and Pizer (2003) and Groom et al (2006) attempt formally to model uncertainty in the discount rate, others argue for a declining scale of discount rates applied over time (e.g., Weitzman 2001, and the UK's "Green Book" for regulatory analysis). This approach uses a higher discount rate

[23] Stern (2008) argues that building in a positive rate of exogenous technical change over time reduces the implied savings rate and that η at or above 2 are inconsistent with observed behavior with regard to equity. (At the same time, adding exogenous technical change—all else equal—would increase g as well.)

initially, but applies a graduated scale of lower discount rates further out in time.[24] A key question that has emerged with regard to both of these approaches is the trade-off between potential time inconsistency and giving greater weight to far future outcomes (see the EPA Science Advisory Board's recent comments on this topic as part of its review of their *Guidelines for Economic Analysis*).[25]

The Discount Rates Selected for Estimating SCC

In light of disagreement in the literature on the appropriate market interest rate to use in this context and uncertainty about how interest rates may change over time, we use three discount rates to span a plausible range of certainty-equivalent constant discount rates: 2.5, 3, and 5 percent per year. Based on the review in the previous sections, the interagency workgroup determined that these three rates reflect reasonable judgments under both descriptive and prescriptive approaches.

The central value, 3 percent, is consistent with estimates provided in the economics literature and OMB's Circular A-4 guidance for the consumption rate of interest. As previously mentioned, the consumption rate of interest is the correct discounting concept to use when future damages from elevated temperatures are estimated in consumption-equivalent units. Further, 3 percent roughly corresponds to the after-tax riskless interest rate. The upper value of 5 percent is included to represent the possibility that climate damages are positively correlated with market returns. Additionally, this discount rate may be justified by the high interest rates that many consumers use to smooth consumption across periods.

The low value, 2.5 percent, is included to incorporate the concern that interest rates are highly uncertain over time. It represents the average certainty-equivalent rate using the mean-reverting and random walk approaches from Newell and Pizer (2003) starting at a discount rate of 3 percent. Using this approach, the certainty equivalent is about 2.2 percent using the random walk model and 2.8 percent using the mean reverting approach.[26] Without giving preference to a particular model, the average of the two rates is 2.5 percent. Further, a rate below the riskless rate would be justified if climate investments are negatively correlated with the overall market rate of return. Use of this lower value also responds to certain judgments using the prescriptive or normative approach and to ethical objections that have been raised about rates of 3 percent or higher.

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[24] For instance, the UK applies a discount rate of 3.5 percent to the first 30 years; 3 percent for years 31 - 75; 2.5 percent for years 76 - 125; 2 percent for years 126 - 200; 1.5 percent for years 201 - 300; and 1 percent after 300 years. As a sensitivity, it recommends a discount rate of 3 percent for the first 30 years, also decreasing over time.

[25] Uncertainty in future damages is distinct from uncertainty in the discount rate. Weitzman (2008) argues that Stern's choice of a low discount rate was "right for the wrong reasons." He demonstrates how the damages from a low probability, catastrophic event far in the future dominate the effect of the discount rate in a present value calculation and result in an infinite willingness-to-pay for mitigation today. Newbold and Daigneault, (2009) and Nordhaus (2009) find that Weitzman's result is sensitive to the functional forms chosen for climate sensitivity, utility, and consumption. Summers and Zeckhauser (2008) argue that uncertainty in future damages can also work in the other direction by increasing the benefits of waiting to learn the appropriate level of mitigation required.

[26] Calculations done by Pizer et al. using the original simulation program from Newell and Pizer (2003).

IV. Revised SCC Estimates

Our general approach to estimating SCC values is to run the three integrated assessment models (FUND, DICE, and PAGE) using the following inputs agreed upon by the interagency group:

- A Roe and Baker distribution for the climate sensitivity parameter bounded between 0 and 10 with a median of 3 °C and a cumulative probability between 2 and 4.5 °C of two-thirds.
- Five sets of GDP, population and carbon emissions trajectories based on EMF-22.
- Constant annual discount rates of 2.5, 3, and 5 percent.

Because the climate sensitivity parameter is modeled probabilistically, and because PAGE and FUND incorporate uncertainty in other model parameters, the final output from each model run is a distribution over the SCC in year *t*.

For each of the IAMS, the basic computational steps for calculating the SCC in a particular year *t* are:

1. Input the path of emissions, GDP, and population from the selected EMF-22 scenarios, and the extrapolations based on these scenarios for post-2100 years.

2. Calculate the temperature effects and (consumption-equivalent) damages in each year resulting from the baseline path of emissions.

   a. In PAGE, the consumption-equivalent damages in each period are calculated as a fraction of the EMF GDP forecast, depending on the temperature in that period relative to the pre-industrial average temperature in each region.
   b. In FUND, damages in each period depend on both the level and the rate of temperature change in that period.
   c. In DICE, temperature affects both consumption and investment, so we first adjust the EMF GDP paths as follows: Using the Cobb-Douglas production function with the DICE2007 parameters, we extract the path of exogenous technical change implied by the EMF GDP and population paths, then we recalculate the baseline GDP path taking into account climate damages resulting from the baseline emissions path.

3. Add an additional unit of carbon emissions in year *t.* (The exact unit varies by model.)

4. Recalculate the temperature effects and damages expected in all years beyond *t* resulting from this adjusted path of emissions, as in step 2.

5. Subtract the damages computed in step 2 from those in step 4 in each year. (DICE is run in 10 year time steps, FUND in annual time steps, while the time steps in PAGE vary.)

6. Discount the resulting path of marginal damages back to the year of emissions using the agreed upon fixed discount rates.

7. Calculate the SCC as the net present value of the discounted path of damages computed in step 6, divided by the unit of carbon emissions used to shock the models in step 3.

8. Multiply by 12/44 to convert from dollars per ton of carbon to dollars per ton of CO_2 (2007 dollars) in DICE and FUND. (All calculations are done in tons of CO_2 in PAGE).

The steps above were repeated in each model for multiple future years to cover the time horizons anticipated for upcoming rulemaking analysis. To maintain consistency across the three IAMs, climate damages are calculated as lost consumption in each future year.

It is important to note that each of the three models has a different default end year. The default time horizon is 2200 for PAGE, 2595 for DICE, and 3000 for the latest version of FUND. This is an issue for the multi-model approach because differences in SCC estimates may arise simply due to the model time horizon. Many consider 2200 too short a time horizon because it could miss a significant fraction of damages under certain assumptions about the growth of marginal damages and discounting, so each model is run here through 2300. This step required a small adjustment in the PAGE model only. This step also required assumptions about GDP, population, and greenhouse gas emission trajectories after 2100, the last year for which these data are available from the EMF-22 models. (A more detailed discussion of these assumptions is included in the Appendix.)

This exercise produces 45 separate distributions of the SCC for a given year, the product of 3 models, 3 discount rates, and 5 socioeconomic scenarios. This is clearly too many separate distributions for consideration in a regulatory impact analysis.

To produce a range of plausible estimates that still reflects the uncertainty in the estimation exercise, the distributions from each of the models and scenarios are equally weighed and combined to produce three separate probability distributions for SCC in a given year, one for each assumed discount rate. These distributions are then used to define a range of point estimates for the global SCC. In this way, no integrated assessment model or socioeconomic scenario is given greater weight than another. Because the literature shows that the SCC is quite sensitive to assumptions about the discount rate, and because no consensus exists on the appropriate rate to use in an intergenerational context, we present SCCs based on the average values across models and socioeconomic scenarios for each discount rate.

The interagency group selected four SCC values for use in regulatory analyses. Three values are based on the average SCC across models and socio-economic and emissions scenarios at the 2.5, 3, and 5 percent discount rates. The fourth value is included to represent the higher-than-expected economic impacts from climate change further out in the tails of the SCC distribution. For this purpose, we use the SCC value for the 95th percentile at a 3 percent discount rate. (The full set of distributions by model and scenario combination is included in the Appendix.) As noted above, the 3 percent discount rate is the central value, and so the central value that emerges is the average SCC across models at the 3 percent discount rate. For purposes of capturing the uncertainties involved in regulatory impact analysis, we emphasize the importance and value of considering the full range.

As previously discussed, low probability, high impact events are incorporated into the SCC values through explicit consideration of their effects in two of the three models as well as the use of a probability density function for equilibrium climate sensitivity. Treating climate sensitivity probabilistically results in more high temperature outcomes, which in turn lead to higher projections of damages. Although FUND does not include catastrophic damages (in contrast to the other two models), its probabilistic treatment of the equilibrium climate sensitivity parameter will directly affect the non-catastrophic damages that are a function of the rate of temperature change.

In Table 3, we begin by presenting SCC estimates for 2010 by model, scenario, and discount rate to illustrate the variability in the SCC across each of these input parameters. As expected, higher discount rates consistently result in lower SCC values, while lower discount rates result in higher SCC values for each socioeconomic trajectory. It is also evident that there are differences in the SCC estimated across the three main models. For these estimates, FUND produces the lowest estimates, while PAGE generally produces the highest estimates.

Table 3: Disaggregated Social Cost of CO_2 Values by Model, Socio-Economic Trajectory, and Discount Rate for 2010 (in 2007 dollars)

	Discount rate:	**5%**	**3%**	**2.5%**	**3%**
Model	*Scenario*	Avg	Avg	Avg	95th
DICE	IMAGE	10.8	35.8	54.2	70.8
	MERGE	7.5	22.0	31.6	42.1
	Message	9.8	29.8	43.5	58.6
	MiniCAM	8.6	28.8	44.4	57.9
	550 Average	8.2	24.9	37.4	50.8
PAGE	IMAGE	8.3	39.5	65.5	142.4
	MERGE	5.2	22.3	34.6	82.4
	Message	7.2	30.3	49.2	115.6
	MiniCAM	6.4	31.8	54.7	115.4
	550 Average	5.5	25.4	42.9	104.7
FUND	IMAGE	-1.3	8.2	19.3	39.7
	MERGE	-0.3	8.0	14.8	41.3
	Message	-1.9	3.6	8.8	32.1
	MiniCAM	-0.6	10.2	22.2	42.6
	550 Average	-2.7	-0.2	3.0	19.4

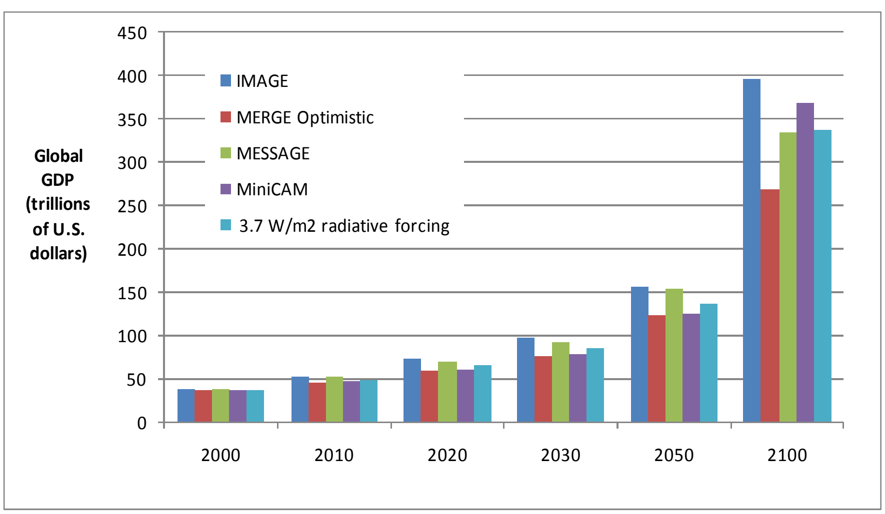
These results are not surprising when compared to the estimates in the literature for the latest versions of each model. For example, adjusting the values from the literature that were used to develop interim

SCC values to 2007 dollars for the year 2010 (assuming, as we did for the interim process, that SCC grows at 3 percent per year), FUND yields SCC estimates at or near zero for a 5 percent discount rate and around \$9 per ton for a 3 percent discount rate. There are far fewer estimates using the latest versions of DICE and PAGE in the literature: Using similar adjustments to generate 2010 estimates, we calculate a SCC from DICE (based on Nordhaus 2008) of around \$9 per ton for a 5 percent discount rate, and a SCC from PAGE (based on Hope 2006, 2008) close to \$8 per ton for a 4 percent discount rate. Note that these comparisons are only approximate since the literature generally relies on Ramsey discounting, while we have assumed constant discount rates.[27]

The SCC estimates from FUND are sensitive to differences in emissions paths but relatively insensitive to differences in GDP paths across scenarios, while the reverse is true for DICE and PAGE. This likely occurs because of several structural differences among the models. Specifically in DICE and PAGE, the fraction of economic output lost due to climate damages increases with the level of temperature alone, whereas in FUND the fractional loss also increases with the rate of temperature change. Furthermore, in FUND increases in income over time decrease vulnerability to climate change (a form of adaptation), whereas this does not occur in DICE and PAGE. These structural differences among the models make FUND more sensitive to the path of emissions and less sensitive to GDP compared to DICE and PAGE.

Figure 3 shows that IMAGE has the highest GDP in 2100 while MERGE Optimistic has the lowest. The ordering of global GDP levels in 2100 directly corresponds to the rank ordering of SCC for PAGE and DICE. For FUND, the correspondence is less clear, a result that is to be expected given its less direct relationship between its damage function and GDP.

Figure 3: Level of Global GDP across EMF Scenarios



[27] Nordhaus (2008) runs DICE2007 with ρ = 1.5 and η = 2. The default approach in PAGE2002 (version 1.4epm) treats ρ and η as random parameters, specified using a triangular distribution such that the min, mode, and max = 0.1, 1, and 2 for ρ, and 0.5, 1, and 2 for η, respectively. The FUND default value for η is 1, and Tol generates SCC estimates for values of ρ = 0, 1, and 3 in many recent papers (e.g. Anthoff et al. 2009). The path of per-capita consumption growth, g, varies over time but is treated deterministically in two of the three models. In DICE, g is endogenous. Under Ramsey discounting, as economic growth slows in the future, the large damages from climate change that occur far out in the future are discounted at a lower rate than impacts that occur in the nearer term.

Table 4 shows the four selected SCC values in five year increments from 2010 to 2050. Values for 2010, 2020, 2040, and 2050 are calculated by first combining all outputs (10,000 estimates per model run) from all scenarios and models for a given discount rate. Values for the years in between are calculated using a simple linear interpolation.

Table 4: Social Cost of CO_2, 2010 – 2050 (in 2007 dollars)

Discount Rate Year	5% Avg	3% Avg	2.5% Avg	3% 95th
2010	4.7	21.4	35.1	64.9
2015	5.7	23.8	38.4	72.8
2020	6.8	26.3	41.7	80.7
2025	8.2	29.6	45.9	90.4
2030	9.7	32.8	50.0	100.0
2035	11.2	36.0	54.2	109.7
2040	12.7	39.2	58.4	119.3
2045	14.2	42.1	61.7	127.8
2050	15.7	44.9	65.0	136.2

The SCC increases over time because future emissions are expected to produce larger incremental damages as physical and economic systems become more stressed in response to greater climatic change. Note that this approach allows us to estimate the growth rate of the SCC directly using DICE, PAGE, and FUND rather than assuming a constant annual growth rate as was done for the interim estimates (using 3 percent). This helps to ensure that the estimates are internally consistent with other modeling assumptions. Table 5 illustrates how the growth rate for these four SCC estimates varies over time. The full set of annual SCC estimates between 2010 and 2050 is reported in the Appendix.

Table 5: Changes in the Average Annual Growth Rates of SCC Estimates between 2010 and 2050

Average Annual Growth Rate (%)	**5%** Avg	**3%** Avg	**2.5%** Avg	**3.0%** 95th
2010-2020	3.6%	2.1%	1.7%	2.2%
2020-2030	3.7%	2.2%	1.8%	2.2%
2030-2040	2.7%	1.8%	1.6%	1.8%
2040-2050	2.1%	1.4%	1.1%	1.3%

While the SCC estimate grows over time, the future monetized value of emissions reductions in each year (the SCC in year *t* multiplied by the change in emissions in year *t*) must be discounted to the present to determine its total net present value for use in regulatory analysis. Damages from future emissions should be discounted at the same rate as that used to calculate the SCC estimates themselves to ensure internal consistency—i.e., future damages from climate change, whether they result from emissions today or emissions in a later year, should be discounted using the same rate. For example, climate damages in the year 2020 that are calculated using a SCC based on a 5 percent discount rate also should be discounted back to the analysis year using a 5 percent discount rate.[28]

V. Limitations of the Analysis

As noted, any estimate of the SCC must be taken as provisional and subject to further refinement (and possibly significant change) in accordance with evolving scientific, economic, and ethical understandings. During the course of our modeling, it became apparent that there are several areas in particular need of additional exploration and research. These caveats, and additional observations in the following section, are necessary to consider when interpreting and applying the SCC estimates.

Incomplete treatment of non-catastrophic damages. The impacts of climate change are expected to be widespread, diverse, and heterogeneous. In addition, the exact magnitude of these impacts is uncertain because of the inherent complexity of climate processes, the economic behavior of current and future populations, and our inability to accurately forecast technological change and adaptation. Current IAMs do not assign value to all of the important physical, ecological, and economic impacts of climate change recognized in the climate change literature (some of which are discussed above) because of lack of precise information on the nature of damages and because the science incorporated into these models understandably lags behind the most recent research. Our ability to quantify and monetize impacts will undoubtedly improve with time. But it is also likely that even in future applications, a number of potentially significant damage categories will remain non-monetized. (Ocean acidification is one example of a potentially large damage from CO_2 emissions not quantified by any of the three models. Species and wildlife loss is another example that is exceedingly difficult to monetize.)

Incomplete treatment of potential catastrophic damages. There has been considerable recent discussion of the risk of catastrophic impacts and how best to account for extreme scenarios, such as the collapse of the Atlantic Meridional Overturning Circulation or the West Antarctic Ice Sheet, or large releases of methane from melting permafrost and warming oceans. Weitzman (2009) suggests that catastrophic damages are extremely large—so large, in fact, that the damages from a low probability, catastrophic event far in the future dominate the effect of the discount rate in a present value calculation and result in an infinite willingness-to-pay for mitigation today. However, Nordhaus (2009) concluded that the conditions under which Weitzman's results hold “are limited and do not apply to a wide range of potential uncertain scenarios."

Using a simplified IAM, Newbold and Daigneault (2009) confirmed the potential for large catastrophe risk premiums but also showed that the aggregate benefit estimates can be highly sensitive to the shapes of both the climate sensitivity distribution and the damage function at high temperature changes. Pindyck (2009) also used a simplified IAM to examine high-impact low-probability risks, using a right-skewed gamma distribution for climate sensitivity as well as an uncertain damage coefficient, but in most cases found only a modest risk premium. Given this difference in opinion, further research in this area is needed before its practical significance can be fully understood and a reasonable approach developed to account for such risks in regulatory analysis. (The next section discusses the scientific evidence on catastrophic impacts in greater detail.)

[28] However, it is possible that other benefits or costs of proposed regulations unrelated to CO_2 emissions will be discounted at rates that differ from those used to develop the SCC estimates.

Uncertainty in extrapolation of damages to high temperatures: The damage functions in these IAMs are typically calibrated by estimating damages at moderate temperature increases (e.g., DICE was calibrated at 2.5 °C) and extrapolated to far higher temperatures by assuming that damages increase as some power of the temperature change. Hence, estimated damages are far more uncertain under more extreme climate change scenarios.

Incomplete treatment of adaptation and technological change: Each of the three integrated assessment models used here assumes a certain degree of low- or no-cost adaptation. For instance, Tol assumes a great deal of adaptation in FUND, including widespread reliance on air conditioning ; so much so, that the largest single benefit category in FUND is the reduced electricity costs from not having to run air conditioning as intensively (NRC 2009).

Climate change also will increase returns on investment to develop technologies that allow individuals to cope with adverse climate conditions, and IAMs to do not adequately account for this directed technological change.[29] For example, scientists may develop crops that are better able to withstand higher and more variable temperatures. Although DICE and FUND have both calibrated their agricultural sectors under the assumption that farmers will change land use practices in response to climate change (Mastrandrea, 2009), they do not take into account technological changes that lower the cost of this adaptation over time. On the other hand, the calibrations do not account for increases in climate variability, pests, or diseases, which could make adaptation more difficult than assumed by the IAMs for a given temperature change. Hence, models do not adequately account for potential adaptation or technical change that might alter the emissions pathway and resulting damages. In this respect, it is difficult to determine whether the incomplete treatment of adaptation and technological change in these IAMs under or overstate the likely damages.

Risk aversion: A key question unanswered during this interagency process is what to assume about relative risk aversion with regard to high-impact outcomes. These calculations do not take into account the possibility that individuals may have a higher willingness to pay to reduce the likelihood of low-probability, high-impact damages than they do to reduce the likelihood of higher-probability but lower-impact damages with the same expected cost. (The inclusion of the 95th percentile estimate in the final set of SCC values was largely motivated by this concern.) If individuals do show such a higher willingness to pay, a further question is whether that fact should be taken into account for regulatory policy. Even if individuals are not risk-averse for such scenarios, it is possible that regulatory policy should include a degree of risk-aversion.

Assuming a risk-neutral representative agent is consistent with OMB's Circular A-4, which advises that the estimates of benefits and costs used in regulatory analysis are usually based on the average or the expected value and that "emphasis on these expected values is appropriate as long as society is 'risk neutral' with respect to the regulatory alternatives. While this may not always be the case, [analysts] should in general assume 'risk neutrality' in [their] analysis."

Nordhaus (2008) points to the need to explore the relationship between risk and income in the context of climate change across models and to explore the role of uncertainty regarding various parameters in

[29] However these research dollars will be diverted from whatever their next best use would have been in the absence of climate change (so productivity/GDP would have been still higher).

the results. Using FUND, Anthoff et al (2009) explored the sensitivity of the SCC to Ramsey equation parameter assumptions based on observed behavior. They conclude that "the assumed rate of risk aversion is at least as important as the assumed rate of time preference in determining the social cost of carbon." Since Circular A-4 allows for a different assumption on risk preference in regulatory analysis if it is adequately justified, we plan to continue investigating this issue.

V. A Further Discussion of Catastrophic Impacts and Damage Functions

As noted above, the damage functions underlying the three IAMs used to estimate the SCC may not capture the economic effects of all possible adverse consequences of climate change and may therefore lead to underestimates of the SCC (Mastrandrea 2009). In particular, the models' functional forms may not adequately capture: (1) potentially discontinuous "tipping point" behavior in Earth systems, (2) inter-sectoral and inter-regional interactions, including global security impacts of high-end warming, and (3) limited near-term substitutability between damage to natural systems and increased consumption.

It is the hope of the interagency group that over time researchers and modelers will work to fill these gaps and that the SCC estimates used for regulatory analysis by the Federal government will continue to evolve with improvements in modeling. In the meantime, we discuss some of the available evidence.

Extrapolation of climate damages to high levels of warming

The damage functions in the models are calibrated at moderate levels of warming and should therefore be viewed cautiously when extrapolated to the high temperatures found in the upper end of the distribution. Recent science suggests that there are a number of potential climatic "tipping points" at which the Earth system may exhibit discontinuous behavior with potentially severe social and economic consequences (e.g., Lenton et al, 2008, Kriegler et al., 2009). These tipping points include the disruption of the Indian Summer Monsoon, dieback of the Amazon Rainforest and boreal forests, collapse of the Greenland Ice Sheet and the West Antarctic Ice Sheet, reorganization of the Atlantic Meridional Overturning Circulation, strengthening of El Niño-Southern Oscillation, and the release of methane from melting permafrost. Many of these tipping points are estimated to have thresholds between about 3 °C and 5 °C (Lenton et al., 2008). Probabilities of several of these tipping points were assessed through expert elicitation in 2005–2006 by Kriegler et al. (2009); results from this study are highlighted in Table 6. Ranges of probability are averaged across core experts on each topic.

As previously mentioned, FUND does not include potentially catastrophic effects. DICE assumes a small probability of catastrophic damages that increases with increased warming, but the damages from these risks are incorporated as expected values (i.e., ignoring potential risk aversion). PAGE models catastrophic impacts in a probabilistic framework (see Figure 1), so the high-end output from PAGE potentially offers the best insight into the SCC if the world were to experience catastrophic climate change. For instance, at the 95th percentile and a 3 percent discount rate, the SCC estimated by PAGE across the five socio-economic and emission trajectories of \$113 per ton of CO_2 is almost double the value estimated by DICE, \$58 per ton in 2010. We cannot evaluate how well the three models account for catastrophic or non-catastrophic impacts, but this estimate highlights the sensitivity of SCC values in the tails of the distribution to the assumptions made about catastrophic impacts.

Table 6: Probabilities of Various Tipping Points from Expert Elicitation -

Possible Tipping Points	Duration before effect is fully realized (in years)	Additional Warming by 2100		
		0.5-1.5 C	1.5-3.0 C	3-5 C
Reorganization of Atlantic Meridional Overturning Circulation	about 100	0-18%	6-39%	18-67%
Greenland Ice Sheet collapse	at least 300	8-39%	33-73%	67-96%
West Antarctic Ice Sheet collapse	at least 300	5-41%	10-63%	33-88%
Dieback of Amazon rainforest	about 50	2-46%	14-84%	41-94%
Strengthening of El Niño-Southern Oscillation	about 100	1-13%	6-32%	19-49%
Dieback of boreal forests	about 50	13-43%	20-81%	34-91%
Shift in Indian Summer Monsoon	about 1	Not formally assessed		
Release of methane from melting permafrost	Less than 100	Not formally assessed.		

PAGE treats the possibility of a catastrophic event probabilistically, while DICE treats it deterministically (that is, by adding the expected value of the damage from a catastrophe to the aggregate damage function). In part, this results in different probabilities being assigned to a catastrophic event across the two models. For instance, PAGE places a probability near zero on a catastrophe at 2.5 °C warming, while DICE assumes a 4 percent probability of a catastrophe at 2.5 °C. By comparison, Kriegler et al. (2009) estimate a probability of at least 16-36 percent of crossing at least one of their primary climatic tipping points in a scenario with temperatures about 2-4 °C warmer than pre-Industrial levels in 2100.

It is important to note that crossing a climatic tipping point will not necessarily lead to an economic catastrophe in the sense used in the IAMs. A tipping point is a critical threshold across which some aspect of the Earth system starts to shifts into a qualitatively different state (for instance, one with dramatically reduced ice sheet volumes and higher sea levels). In the IAMs, a catastrophe is a low-probability environmental change with high economic impact.

Failure to incorporate inter-sectoral and inter-regional interactions

The damage functions do not fully incorporate either inter-sectoral or inter-regional interactions. For instance, while damages to the agricultural sector are incorporated, the effects of changes in food supply on human health are not fully captured and depend on the modeler's choice of studies used to calibrate the IAM. Likewise, the effects of climate damages in one region of the world on another region are not included in some of the models (FUND includes the effects of migration from sea level rise). These inter-regional interactions, though difficult to quantify, are the basis for climate-induced national and economic security concerns (e.g., Campbell et al., 2007; U.S. Department of Defense 2010) and are particularly worrisome at higher levels of warming. High-end warming scenarios, for instance, project water scarcity affecting 4.3-6.9 billion people by 2050, food scarcity affecting about 120 million additional people by 2080, and the creation of millions of climate refugees (Easterling et al., 2007; Campbell et al., 2007).

Imperfect substitutability of environmental amenities

Data from the geological record of past climate changes suggests that 6 °C of warming may have severe consequences for natural systems. For instance, during the Paleocene-Eocene Thermal Maximum about 55.5 million years ago, when the Earth experienced a geologically rapid release of carbon associated with an approximately 5 °C increase in global mean temperatures, the effects included shifts of about 400-900 miles in the range of plants (Wing et al., 2005), and dwarfing of both land mammals (Gingerich, 2006) and soil fauna (Smith et al., 2009).

The three IAMs used here assume that it is possible to compensate for the economic consequences of damages to natural systems through increased consumption of non-climate goods, a common assumption in many economic models. In the context of climate change, however, it is possible that the damages to natural systems could become so great that no increase in consumption of non-climate goods would provide complete compensation (Levy et al., 2005). For instance, as water supplies become scarcer or ecosystems become more fragile and less bio-diverse, the services they provide may become increasingly more costly to replace. Uncalibrated attempts to incorporate the imperfect substitutability of such amenities into IAMs (Sterner and Persson, 2008) indicate that the optimal degree of emissions abatement can be considerably greater than is commonly recognized.

VI. Conclusion

The interagency group selected four SCC estimates for use in regulatory analyses. For 2010, these estimates are $5, $21, $35, and $65 (in 2007 dollars). The first three estimates are based on the average SCC across models and socio-economic and emissions scenarios at the 5, 3, and 2.5 percent discount rates, respectively. The fourth value is included to represent the higher-than-expected impacts from temperature change further out in the tails of the SCC distribution. For this purpose, we use the SCC value for the 95th percentile at a 3 percent discount rate. The central value is the average SCC across models at the 3 percent discount rate. For purposes of capturing the uncertainties involved in regulatory impact analysis, we emphasize the importance and value of considering the full range. These SCC estimates also grow over time. For instance, the central value increases to $24 per ton of CO_2 in 2015 and $26 per ton of CO_2 in 2020.

We noted a number of limitations to this analysis, including the incomplete way in which the integrated assessment models capture catastrophic and non-catastrophic impacts, their incomplete treatment of adaptation and technological change, uncertainty in the extrapolation of damages to high temperatures, and assumptions regarding risk aversion. The limited amount of research linking climate impacts to economic damages makes this modeling exercise even more difficult. It is the hope of the interagency group that over time researchers and modelers will work to fill these gaps and that the SCC estimates used for regulatory analysis by the Federal government will continue to evolve with improvements in modeling.

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Appendix

Table A1: Annual SCC Values: 2010–2050 (in 2007 dollars)

Discount Rate Year	5% Avg	3% Avg	2.5% Avg	3% 95th
2010	4.7	21.4	35.1	64.9
2011	4.9	21.9	35.7	66.5
2012	5.1	22.4	36.4	68.1
2013	5.3	22.8	37.0	69.6
2014	5.5	23.3	37.7	71.2
2015	5.7	23.8	38.4	72.8
2016	5.9	24.3	39.0	74.4
2017	6.1	24.8	39.7	76.0
2018	6.3	25.3	40.4	77.5
2019	6.5	25.8	41.0	79.1
2020	6.8	26.3	41.7	80.7
2021	7.1	27.0	42.5	82.6
2022	7.4	27.6	43.4	84.6
2023	7.7	28.3	44.2	86.5
2024	7.9	28.9	45.0	88.4
2025	8.2	29.6	45.9	90.4
2026	8.5	30.2	46.7	92.3
2027	8.8	30.9	47.5	94.2
2028	9.1	31.5	48.4	96.2
2029	9.4	32.1	49.2	98.1
2030	9.7	32.8	50.0	100.0
2031	10.0	33.4	50.9	102.0
2032	10.3	34.1	51.7	103.9
2033	10.6	34.7	52.5	105.8
2034	10.9	35.4	53.4	107.8
2035	11.2	36.0	54.2	109.7
2036	11.5	36.7	55.0	111.6
2037	11.8	37.3	55.9	113.6
2038	12.1	37.9	56.7	115.5
2039	12.4	38.6	57.5	117.4
2040	12.7	39.2	58.4	119.3
2041	13.0	39.8	59.0	121.0
2042	13.3	40.4	59.7	122.7
2043	13.6	40.9	60.4	124.4
2044	13.9	41.5	61.0	126.1
2045	14.2	42.1	61.7	127.8
2046	14.5	42.6	62.4	129.4
2047	14.8	43.2	63.0	131.1
2048	15.1	43.8	63.7	132.8
2049	15.4	44.4	64.4	134.5
2050	15.7	44.9	65.0	136.2

This Appendix also provides additional technical information about the non-CO_2 emission projections used in the modeling and the method for extrapolating emissions forecasts through 2300, and shows the full distribution of 2010 SCC estimates by model and scenario combination.

1. Other (non-CO_2) gases

In addition to fossil and industrial CO_2 emissions, each EMF scenario provides projections of methane (CH_4), nitrous oxide (N_2O), fluorinated gases, and net land use CO_2 emissions to 2100. These assumptions are used in all three IAMs while retaining each model's default radiative forcings (RF) due to other factors (e.g., aerosols and other gases). Specifically, to obtain the RF associated with the non-CO_2 EMF emissions only, we calculated the RF associated with the EMF atmospheric CO_2 concentrations and subtracted them from the EMF total RF.[30] This approach respects the EMF scenarios as much as possible and at the same time takes account of those components not included in the EMF projections. Since each model treats non-CO_2 gases differently (e.g., DICE lumps all other gases into one composite exogenous input), this approach was applied slightly differently in each of the models.

<u>FUND</u>: Rather than relying on RF for these gases, the actual emissions from each scenario were used in FUND. The model default trajectories for CH_4, N_20, SF_6, and the CO_2 emissions from land were replaced with the EMF values.

<u>PAGE</u>: PAGE models CO_2, CH_4, sulfur hexafluoride (SF_6), and aerosols and contains an "excess forcing" vector that includes the RF for everything else. To include the EMF values, we removed the default CH_4 and SF_6 factors[31], decomposed the excess forcing vector, and constructed a new excess forcing vector that includes the EMF RF for CH_4, N_20, and fluorinated gases, as well as the model default values for aerosols and other factors. Net land use CO_2 emissions were added to the fossil and industrial CO_2 emissions pathway.

<u>DICE</u>: DICE presents the greatest challenge because all forcing due to factors other than industrial CO_2 emissions is embedded in an exogenous non-CO_2 RF vector. To decompose this exogenous forcing path into EMF non-CO_2 gases and other gases, we relied on the references in DICE2007 to the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report (AR4) and the discussion of aerosol forecasts in the IPCC's Third Assessment Report (TAR) and in AR4, as explained below. In DICE2007, Nordhaus assumes that exogenous forcing from all non-CO_2 sources is -0.06 W/m^2 in 2005, as reported in AR4, and increases linearly to 0.3 W/m^2 in 2105, based on GISS projections, and then stays constant after that time.

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[30] Note EMF did not provide CO_2 concentrations for the IMAGE reference scenario. Thus, for this scenario, we fed the fossil, industrial and land CO_2 emissions into MAGICC (considered a "neutral arbiter" model, which is tuned to emulate the major global climate models) and the resulting CO_2 concentrations were used. Note also that MERGE assumes a neutral biosphere so net land CO_2 emissions are set to zero for all years for the MERGE Optimistic reference scenario, and for the MERGE component of the average 550 scenario (i.e., we add up the land use emissions from the other three models and divide by 4).

[31] Both the model default CH_4 emissions and the initial atmospheric CH_4 is set to zero to avoid double counting the effect of past CH_4 emissions.

According to AR4, the RF in 2005 from CH_4, N_20, and halocarbons (approximately similar to the F-gases in the EMF-22 scenarios) was 0.48 + 0.16 + 0.34 = 0.98 W/m^2 and RF from total aerosols was -1.2 W/m^2. Thus, the -.06 W/m^2 non-CO_2 forcing in DICE can be decomposed into: 0.98 W/m^2 due to the EMF non-CO_2 gases, -1.2 W/m^2 due to aerosols, and the remainder, 0.16 W/m^2, due to other residual forcing.

For subsequent years, we calculated the DICE default RF from aerosols and other non-CO_2 gases based on the following two assumptions:

(1) RF from aerosols declines linearly from 2005 to 2100 at the rate projected by the TAR and then stays constant thereafter, and
(2) With respect to RF from non-CO_2 gases not included in the EMF-22 scenarios, the share of non-aerosol RF matches the share implicit in the AR4 summary statistics cited above and remains constant over time.

Assumption (1) means that the RF from aerosols in 2100 equals 66 percent of that in 2000, which is the fraction of the TAR projection of total RF from aerosols (including sulfates, black carbon, and organic carbon) in 2100 vs. 2000 under the A1B SRES emissions scenario. Since the SRES marker scenarios were not updated for the AR4, the TAR provides the most recent IPCC projection of aerosol forcing. We rely on the A1B projection from the TAR because it provides one of the lower aerosol forecasts among the SRES marker scenarios and is more consistent with the AR4 discussion of the post-SRES literature on aerosols:

> *Aerosols have a net cooling effect and the representation of aerosol and aerosol precursor emissions, including sulphur dioxide, black carbon and organic carbon, has improved in the post-SRES scenarios. Generally, these emissions are projected to be lower than reported in SRES. {WGIII 3.2, TS.3, SPM}.*[32]

Assuming a simple linear decline in aerosols from 2000 to 2100 also is more consistent with the recent literature on these emissions. For example, Figure A1 shows that the sulfur dioxide emissions peak over the short-term of some SRES scenarios above the upper bound estimates of the more recent scenarios.[33] Recent scenarios project sulfur emissions to peak earlier and at lower levels compared to the SRES in part because of new information about present and planned sulfur legislation in some developing countries, such as India and China.[34] The lower bound projections of the recent literature have also shifted downward slightly compared to the SRES scenario (IPCC 2007).

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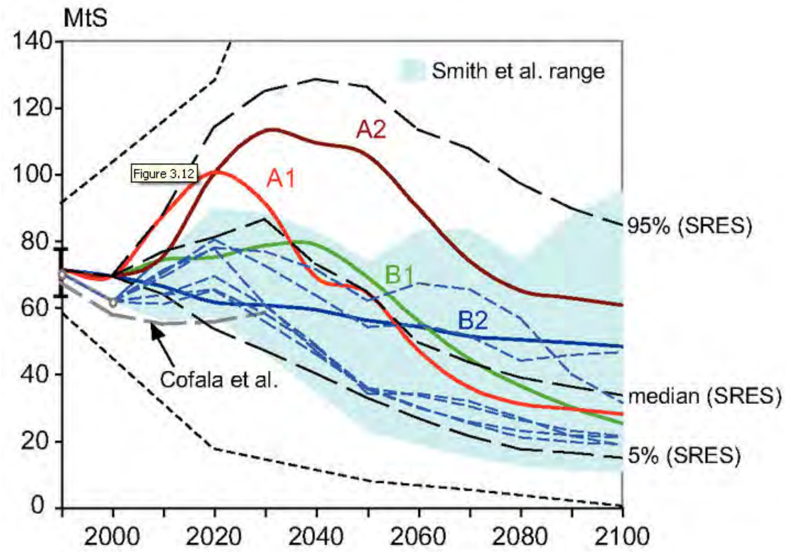
[32] AR4 Synthesis Report, p. 44, http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf

[33] See Smith, S.J., R. Andres, E. Conception, and J. Lurz, 2004: Historical sulfur dioxide emissions, 1850-2000: methods and results. Joint Global Research Institute, College Park, 14 pp.

[34] See Carmichael, G., D. Streets, G. Calori, M. Amann, M. Jacobson, J. Hansen, and H. Ueda, 2002: Changing trends in sulphur emissions in Asia: implications for acid deposition, air pollution, and climate. Environmental Science and Technology, 36(22):4707- 4713; Streets, D., K. Jiang, X. Hu, J. Sinton, X.-Q. Zhang, D. Xu, M. Jacobson, and J. Hansen, 2001: Recent reductions in China's greenhouse gas emissions. Science, 294(5548): 1835-1837.

With these assumptions, the DICE aerosol forcing changes from -1.2 in 2005 to -0.792 in 2105 W/m^2; forcing due to other non-CO_2 gases not included in the EMF scenarios declines from 0.160 to 0.153 W/m^2.

Figure A1: Sulphur Dioxide Emission Scenarios -



Notes: Thick colored lines depict the four SRES marker scenarios and black dashed lines show the median, 5th and 95th percentile of the frequency distribution for the full ensemble of 40 SRES scenarios. The blue area (and the thin dashed lines in blue) illustrates individual scenarios and the range of Smith et al. (2004). Dotted lines indicate the minimum and maximum of SO_2 emissions scenarios developed pre-SRES.
Source: IPCC (2007), AR4 WGIII 3.2, http://www.ipcc.ch/publications_and_data/ar4/wg3/en/ch3-ens3-2-2-4.html.

Although other approaches to decomposing the DICE exogenous forcing vector are possible, initial sensitivity analysis suggests that the differences among reasonable alternative approaches are likely to be minor. For example, adjusting the TAR aerosol projection above to assume that aerosols will be maintained at 2000 levels through 2100 reduces average SCC values (for 2010) by approximately 3 percent (or less than \$2); assuming all aerosols are phased out by 2100 increases average 2010 SCC values by 6-7 percent (or \$0.50-\$3)–depending on the discount rate. These differences increase slightly for SCC values in later years but are still well within 10 percent of each other as far out as 2050.

Finally, as in PAGE, the EMF net land use CO_2 emissions are added to the fossil and industrial CO_2 emissions pathway.

2. - Extrapolating Emissions Projections to 2300

To run each model through 2300 requires assumptions about GDP, population, greenhouse gas emissions, and radiative forcing trajectories after 2100, the last year for which these projections are available from the EMF-22 models. These inputs were extrapolated from 2100 to 2300 as follows:

1. Population growth rate declines linearly, reaching zero in the year 2200.
2. GDP/ per capita growth rate declines linearly, reaching zero in the year 2300.
3. The decline in the fossil and industrial carbon intensity (CO_2/GDP) growth rate over 2090-2100 is maintained from 2100 through 2300.
4. Net land use CO_2 emissions decline linearly, reaching zero in the year 2200.
5. Non-CO_2 radiative forcing remains constant after 2100.

Long run stabilization of GDP per capita was viewed as a more realistic simplifying assumption than a linear or exponential extrapolation of the pre-2100 economic growth rate of each EMF scenario. This is based on the idea that increasing scarcity of natural resources and the degradation of environmental sinks available for assimilating pollution from economic production activities may eventually overtake the rate of technological progress. Thus, the overall rate of economic growth may slow over the very long run. The interagency group also considered allowing an exponential decline in the growth rate of GDP per capita. However, since this would require an additional assumption about how close to zero the growth rate would get by 2300, the group opted for the simpler and more transparent linear extrapolation to zero by 2300.

The population growth rate is also assumed to decline linearly, reaching zero by 2200. This assumption is reasonably consistent with the United Nations long run population forecast, which estimates global population to be fairly stable after 2150 in the medium scenario (UN 2004).[35] The resulting range of EMF population trajectories (Figure A2) also encompass the UN medium scenario forecasts through 2300 – global population of 8.5 billion by 2200, and 9 billion by 2300.

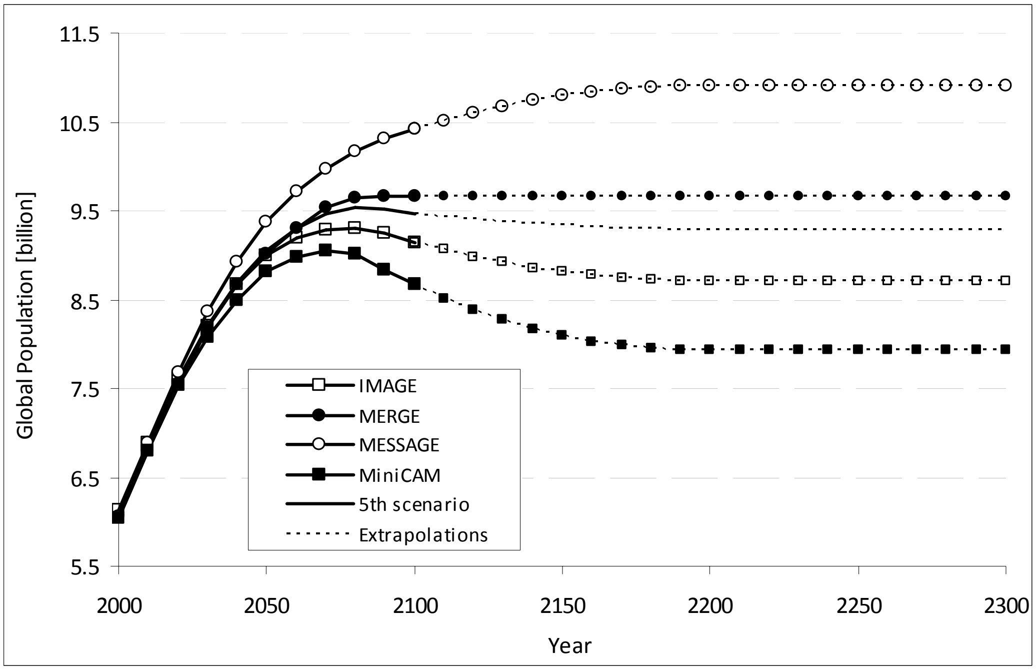
Maintaining the decline in the 2090-2100 carbon intensity growth rate (i.e., CO_2 per dollar of GDP) through 2300 assumes that technological improvements and innovations in the areas of energy efficiency and other carbon reducing technologies (possibly including currently unavailable methods) will continue to proceed at roughly the same pace that is projected to occur towards the end of the forecast period for each EMF scenario. This assumption implies that total cumulative emissions in 2300 will be between 5,000 and 12,000 GtC, which is within the range of the total potential global carbon stock estimated in the literature.

Net land use CO_2 emissions are expected to stabilize in the long run, so in the absence of any post 2100 projections, the group assumed a linear decline to zero by 2200. Given no a priori reasons for assuming a long run increase or decline in non-CO_2 radiative forcing, it is assumed to remain at the 2100 levels for each EMF scenario through 2300.

Figures A2-A7 show the paths of global population, GDP, fossil and industrial CO_2 emissions, net land CO_2 emissions, non-CO_2 radiative forcing, and CO_2 intensity (fossil and industrial CO_2 emissions/GDP) resulting from these assumptions.

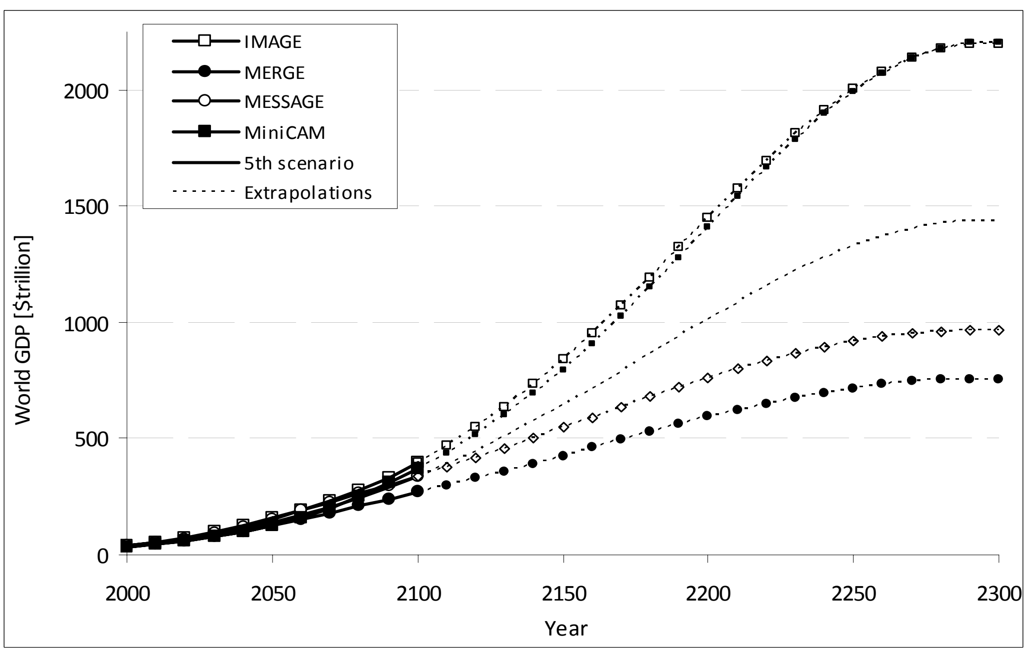
[35] United Nations. 2004. *World Population to 2300*.
http://www.un.org/esa/population/publications/longrange2/worldpop2300final.pdf

Figure A2. Global Population, 2000-2300 (Post-2100 extrapolations assume the population growth rate changes linearly to reach a zero growth rate by 2200.)



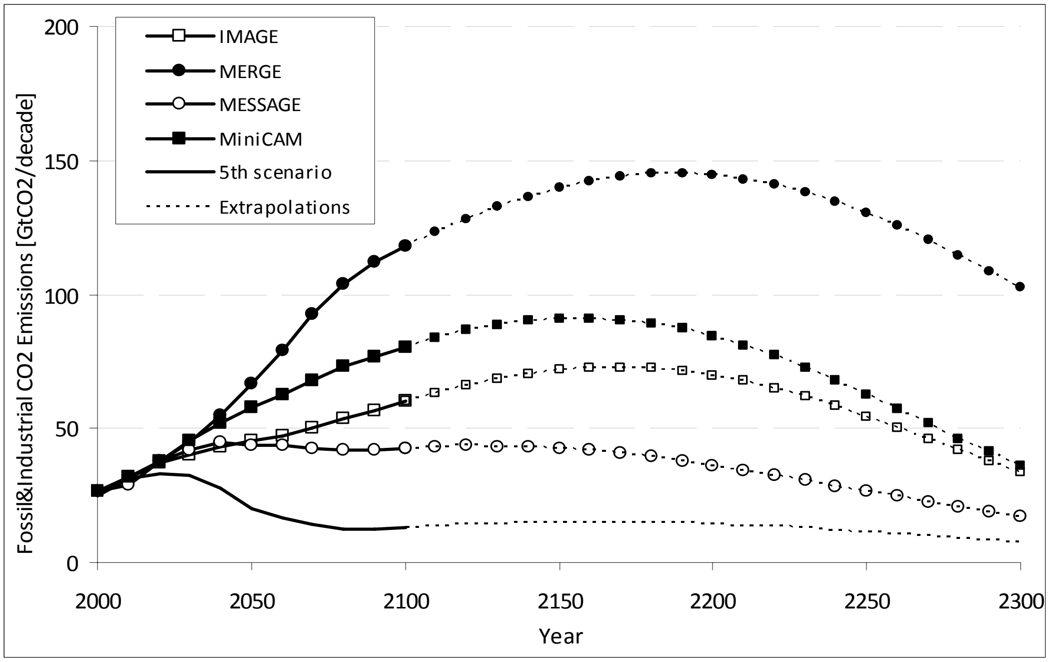
Note: In the fifth scenario, 2000-2100 population is equal to the average of the population under the 550 ppm CO_2e, full-participation, not-to-exceed scenarios considered by each of the four models.

Figure A3. World GDP, 2000-2300 (Post-2100 extrapolations assume GDP per capita growth declines linearly, reaching zero in the year 2300)



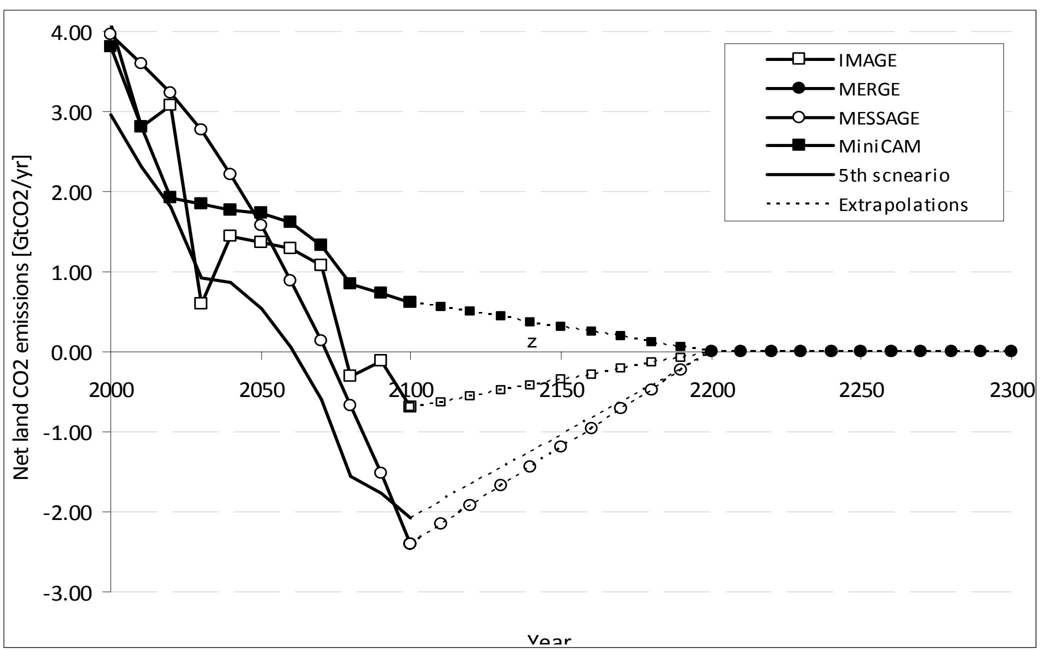
Note: In the fifth scenario, 2000-2100 GDP is equal to the average of the GDP under the 550 ppm CO_2e, full-participation, not-to-exceed scenarios considered by each of the four models.

Figure A4. Global Fossil and Industrial CO_2 Emissions, 2000-2300 (Post-2100 extrapolations assume growth rate of CO_2 intensity (CO_2/GDP) over 2090-2100 is maintained through 2300.)



Note: In the fifth scenario, 2000-2100 emissions are equal to the average of the emissions under the 550 ppm CO2e, full-participation, not-to-exceed scenarios considered by each of the four models.

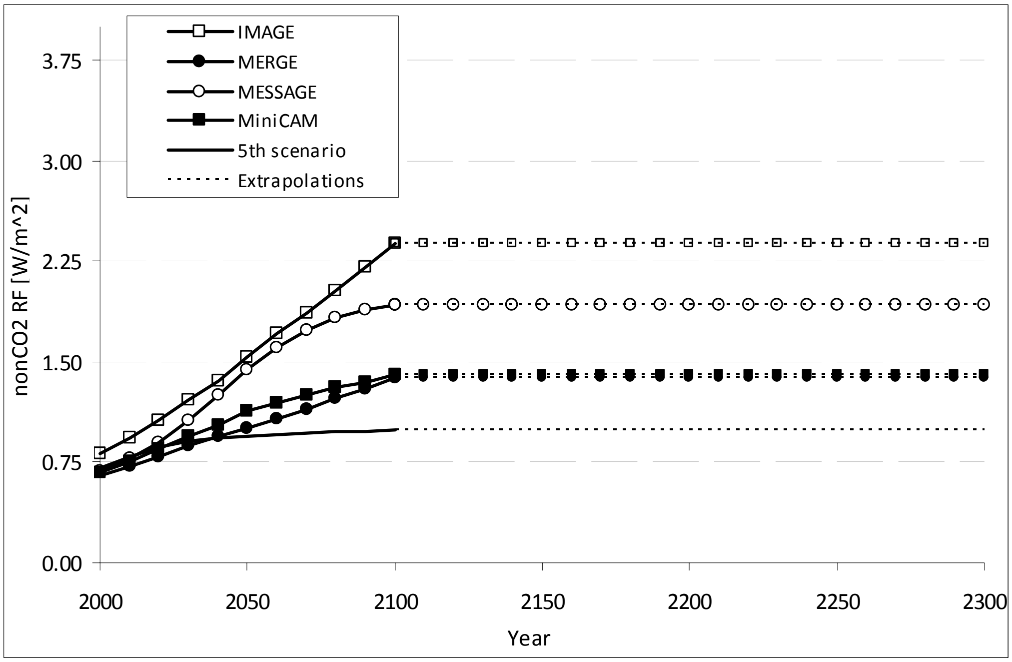
Figure A5. Global Net Land Use CO_2 Emissions, 2000-2300 (Post-2100 extrapolations assume emissions decline linearly, reaching zero in the year 2200)[36]



Note: In the fifth scenario, 2000-2100 emissions are equal to the average of the emissions under the 550 ppm CO2e, full-participation, not-to-exceed scenarios considered by each of the four models.

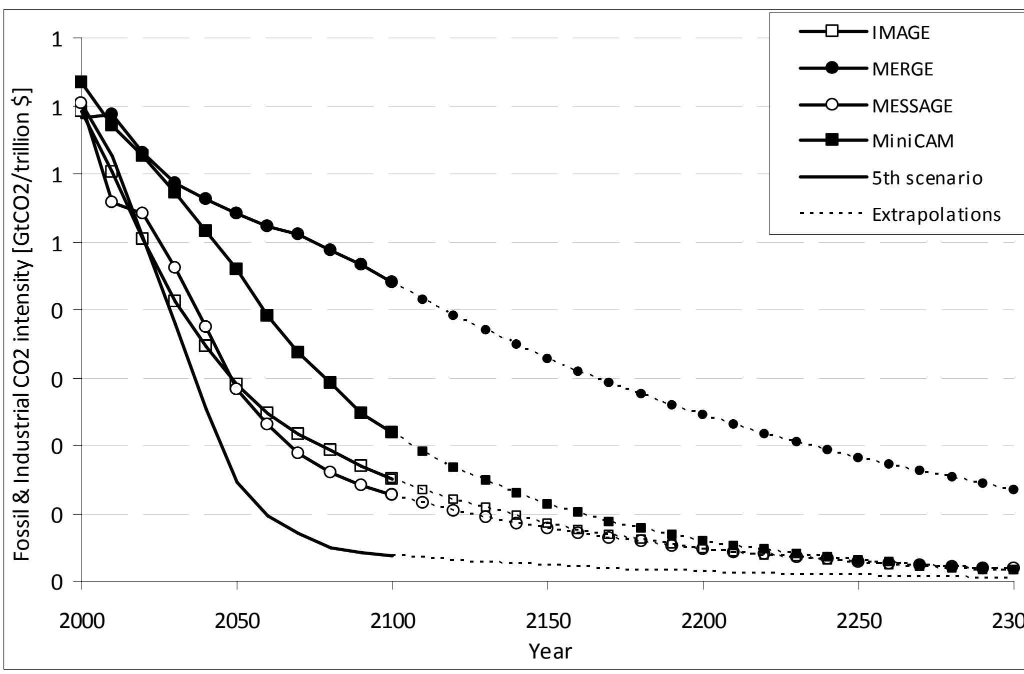
[36] MERGE assumes a neutral biosphere so net land CO_2 emissions are set to zero for all years for the MERGE Optimistic reference scenario, and for the MERGE component of the average 550 scenario (i.e., we add up the land use emissions from the other three models and divide by 4).

Figure A6. Global Non-CO_2 Radiative Forcing, 2000-2300 (Post-2100 extrapolations assume constant non-CO_2 radiative forcing after 2100.)



Note: In the fifth scenario, 2000-2100 emissions are equal to the average of the emissions under the 550 ppm CO2e, full-participation, not-to-exceed scenarios considered by each of the four models.

Figure A7. Global CO_2 Intensity (fossil & industrial CO_2 emissions/GDP), 2000-2300 (Post-2100 extrapolations assume decline in CO_2/GDP growth rate over 2090-2100 is maintained through 2300.)



Note: In the fifth scenario, 2000-2100 emissions are equal to the average of the emissions under the 550 ppm CO_2e, full-participation, not-to-exceed scenarios considered by each of the four models.

Table A2. 2010 Global SCC Estimates at 2.5 Percent Discount Rate (2007$/ton CO_2)

Percentile	1st	5th	10th	25th	50th	Avg	75th	90th	95th	99th
Scenario					**PAGE**					
IMAGE	3.3	5.9	8.1	13.9	28.8	65.5	68.2	147.9	239.6	563.8
MERGE optimistic	1.9	3.2	4.3	7.2	14.6	34.6	36.2	79.8	124.8	288.3
Message	2.4	4.3	5.8	9.8	20.3	49.2	50.7	114.9	181.7	428.4
MiniCAM base	2.7	4.6	6.4	11.2	22.8	54.7	55.7	120.5	195.3	482.3
5th scenario	2.0	3.5	4.7	8.1	16.3	42.9	41.5	103.9	176.3	371.9

Scenario					**DICE**					
IMAGE	16.4	21.4	25	33.3	46.8	54.2	69.7	96.3	111.1	130.0
MERGE optimistic	9.7	12.6	14.9	19.7	27.9	31.6	40.7	54.5	63.5	73.3
Message	13.5	17.2	20.1	27	38.5	43.5	55.1	75.8	87.9	103.0
MiniCAM base	13.1	16.7	19.8	26.7	38.6	44.4	56.8	79.5	92.8	109.3
5th scenario	10.8	14	16.7	22.2	32	37.4	47.7	67.8	80.2	96.8

Scenario					**FUND**					
IMAGE	-33.1	-18.9	-13.3	-5.5	4.1	19.3	18.7	43.5	67.1	150.7
MERGE optimistic	-33.1	-14.8	-10	-3	5.9	14.8	20.4	43.9	65.4	132.9
Message	-32.5	-19.8	-14.6	-7.2	1.5	8.8	13.8	33.7	52.3	119.2
MiniCAM base	-31.0	-15.9	-10.7	-3.4	6	22.2	21	46.4	70.4	152.9
5th scenario	-32.2	-21.6	-16.7	-9.7	-2.3	3	6.7	20.5	34.2	96.8

Table A3. 2010 Global SCC Estimates at 3 Percent Discount Rate (2007$/ton CO_2)

Percentile	1st	5th	10th	25th	50th	Avg	75th	90th	95th	99th
Scenario					**PAGE**					
IMAGE	2.0	3.5	4.8	8.1	16.5	39.5	41.6	90.3	142.4	327.4
MERGE optimistic	1.2	2.1	2.8	4.6	9.3	22.3	22.8	51.3	82.4	190.0
Message	1.6	2.7	3.6	6.2	12.5	30.3	31	71.4	115.6	263.0
MiniCAM base	1.7	2.8	3.8	6.5	13.2	31.8	32.4	72.6	115.4	287.0
5th scenario	1.3	2.3	3.1	5	9.6	25.4	23.6	62.1	104.7	222.5

Scenario					**DICE**					
IMAGE	11.0	14.5	17.2	22.8	31.6	35.8	45.4	61.9	70.8	82.1
MERGE optimistic	7.1	9.2	10.8	14.3	19.9	22	27.9	36.9	42.1	48.8
Message	9.7	12.5	14.7	19	26.6	29.8	37.8	51.1	58.6	67.4
MiniCAM base	8.8	11.5	13.6	18	25.2	28.8	36.9	50.4	57.9	67.8
5th scenario	7.9	10.1	11.8	15.6	21.6	24.9	31.8	43.7	50.8	60.6

Scenario					**FUND**					
IMAGE	-25.2	-15.3	-11.2	-5.6	0.9	8.2	10.4	25.4	39.7	90.3
MERGE optimistic	-24.0	-12.4	-8.7	-3.6	2.6	8	12.2	27	41.3	85.3
Message	-25.3	-16.2	-12.2	-6.8	-0.5	3.6	7.7	20.1	32.1	72.5
MiniCAM base	-23.1	-12.9	-9.3	-4	2.4	10.2	12.2	27.7	42.6	93.0
5th scenario	-24.1	-16.6	-13.2	-8.3	-3	-0.2	2.9	11.2	19.4	53.6

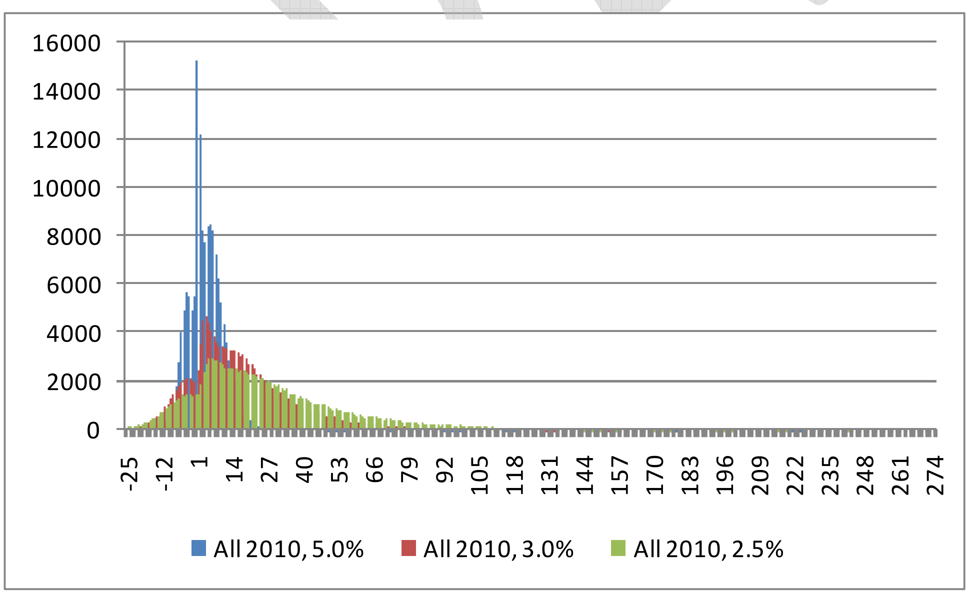
Table A4. 2010 Global SCC Estimates at 5 Percent Discount Rate (2007$/ton CO_2)

Percentile	1st	5th	10th	25th	50th	Avg	75th	90th	95th	99th
Scenario						**PAGE**				
IMAGE	0.5	0.8	1.1	1.8	3.5	8.3	8.5	19.5	31.4	67.2
MERGE optimistic	0.3	0.5	0.7	1.2	2.3	5.2	5.4	12.3	19.5	42.4
Message	0.4	0.7	0.9	1.6	3	7.2	7.2	17	28.2	60.8
MiniCAM base	0.3	0.6	0.8	1.4	2.7	6.4	6.6	15.9	24.9	52.6
5th scenario	0.3	0.6	0.8	1.3	2.3	5.5	5	12.9	22	48.7

Scenario						**DICE**				
IMAGE	4.2	5.4	6.2	7.6	10	10.8	13.4	16.8	18.7	21.1
MERGE optimistic	2.9	3.7	4.2	5.3	7	7.5	9.3	11.7	12.9	14.4
Message	3.9	4.9	5.5	7	9.2	9.8	12.2	15.4	17.1	18.8
MiniCAM base	3.4	4.2	4.7	6	7.9	8.6	10.7	13.5	15.1	16.9
5th scenario	3.2	4	4.6	5.7	7.6	8.2	10.2	12.8	14.3	16.0

Scenario						**FUND**				
IMAGE	-11.7	-8.4	-6.9	-4.6	-2.2	-1.3	0.7	4.1	7.4	17.4
MERGE optimistic	-10.6	-7.1	-5.6	-3.6	-1.3	-0.3	1.6	5.4	9.1	19.0
Message	-12.2	-8.9	-7.3	-4.9	-2.5	-1.9	0.3	3.5	6.5	15.6
MiniCAM base	-10.4	-7.2	-5.8	-3.8	-1.5	-0.6	1.3	4.8	8.2	18.0
5th scenario	-10.9	-8.3	-7	-5	-2.9	-2.7	-0.8	1.4	3.2	9.2

Figure A8. Histogram of Global SCC Estimates in 2010 (2007$/ton CO_2), by discount rate



* The distribution of SCC values ranges from -$5,192 to $66,116 but the X-axis has been truncated at approximately the 1st and 99th percentiles to better show the data.

Table A5. Additional Summary Statistics of 2010 Global SCC Estimates -

Discount rate:	5%				3%				2.5%			
Scenario	Mean	Variance	Skewness	Kurtosis	Mean	Variance	Skewness	Kurtosis	Mean	Variance	Skewness	Kurtosis
DICE	9.0	13.1	0.8	0.2	28.3	209.8	1.1	0.9	42.2	534.9	1.2	1.1
PAGE	6.5	136.0	6.3	72.4	29.8	3,383.7	8.6	151.0	49.3	9,546.0	8.7	143.8
FUND	-1.3	70.1	28.2	1,479.0	6.0	16,382.5	128.0	18,976.5	13.6	150,732.6	149.0	23,558.3

in South Africa (*2*) is one example of an inclusive program that welcomes all but strives to help those who are less prepared. The ENGAGE curriculum gradually increases the volume of work over five years to help students adjust to life at the university. The students are provided with mentoring and other forms of academic and social support, including peer-to-peer interactions. This program has documented stunning success for students from underrepresented groups (*3*), such as black students from poor townships, and the concept may merit serious consideration by other colleges and universities.

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10.1126/science.aao4525

Best cost estimate of greenhouse gases

In March, President Trump's Executive Order 13783 disbanded the Interagency Working Group on the Social Cost of Greenhouse Gases (IWG) (*1*). IWG developed estimates for federal agencies to use in cost-benefit analyses of climate policies. IWG's most recent central estimate was $50 in global damages per ton of carbon dioxide, based on year 2020 emissions, converted from 2007 to 2017 dollars (*2*). Trump's Executive Order withdrew IWG's official valuations and instead instructed agencies to monetize climate effects using "the best available science and economics" (*1*). Yet IWG's estimates already are the product of the most widely peer-reviewed models and best available data (*3*).

The Executive Order asks agencies to reconsider "appropriate discount rates" (the factor for converting future costs and benefits into present-day values) and "domestic versus international impacts" (*1*). These instructions implicitly question IWG's choices to base central estimates on a 3% instead of a 7% discount rate (higher discount rates place less value on avoiding future damages) and to value global damages rather than ignore climate effects beyond U.S. borders. However, scientists and economists widely endorse these methodological choices. The National Academies of Sciences and the U.S. Council of Economic Advisers (*4*, *5*) strongly support a 3% or lower discount rate for intergenerational effects. A 7% rate based on private capital returns is considered inappropriate because the risk profiles of climate effects differ from private investments (*6*, *7*). Most economists and climate policy experts [though not all (*8*)] also defend valuing the full global externalities of U.S. emissions to reinforce reciprocal climate policies in other countries (*3*, *4*, *9*). Moreover, current models cannot accurately estimate a domestic-only share of the social cost of greenhouse gases (*4*, *9*).

The social cost of greenhouse gases should be regularly updated, especially to reflect the latest evidence about damage functions (*10*). Meanwhile, government and private sector analysts should continue using IWG's central estimate of $50 per ton of carbon dioxide with confidence that it is still the best estimate of the social cost of greenhouse gases.

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Science

Best cost estimate of greenhouse gases

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Technical Support Document: -
Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis -
Under Executive Order 12866 -

Interagency Working Group on Social Cost of Greenhouse Gases, United States Government

With participation by

Council of Economic Advisers
Council on Environmental Quality
Department of Agriculture
Department of Commerce
Department of Energy
Department of the Interior
Department of Transportation
Department of the Treasury
Environmental Protection Agency
National Economic Council
Office of Management and Budget
Office of Science and Technology Policy

August 2016

See Appendix B for Details on Revisions since May 2013

Preface

The Interagency Working Group on the Social Cost of Greenhouse Gases (formerly the Interagency Working Group on the Social Cost of Carbon) has a longstanding commitment to ensure that the social cost of carbon estimates continue to reflect the best available science and methodologies. Given this commitment and public comments on issues of a deeply technical nature received by the Office of Management and Budget and federal agencies, the Interagency Working Group is seeking independent expert advice on technical opportunities to update the social cost of carbon estimates. The Interagency Working Group asked the National Academies of Sciences, Engineering, and Medicine in 2015 to review the latest research on modeling the economic aspects of climate change to inform future revisions to the social cost of carbon estimates presented in this technical support document. In January 2016, the Academies' Committee on the Social Cost of Carbon issued an interim report that recommended against a near-term update to the social cost of carbon estimates, but included recommendations for enhancing the presentation and discussion of uncertainty around the current estimates. This revision to the TSD responds to these recommendations in the presentation of the current estimates. It does not revisit the interagency group's 2010 methodological decisions or update the schedule of social cost of carbon estimates presented in the July 2015 revision. The Academies' final report (expected in early 2017) will provide longer term recommendations for a more comprehensive update.

Executive Summary

Executive Order 12866 requires agencies, to the extent permitted by law, "to assess both the costs and the benefits of the intended regulation and, recognizing that some costs and benefits are difficult to quantify, propose or adopt a regulation only upon a reasoned determination that the benefits of the intended regulation justify its costs." The purpose of the social cost of carbon (SC-CO_2)[1] estimates presented here is to allow agencies to incorporate the social benefits of reducing carbon dioxide (CO_2) emissions into cost-benefit analyses of regulatory actions. The SC-CO_2 is the monetized damages associated with an incremental increase in carbon emissions in a given year. It is intended to include (but is not limited to) changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services due to climate change.

The interagency process that developed the original U.S. government SC-CO_2 estimates is described in the 2010 Technical Support Document on the Social Cost of Carbon (TSD) (Interagency Working Group on Social Cost of Carbon 2010). Through that process the Interagency Working Group (IWG) selected SC-CO_2 values for use in regulatory analyses. For each emissions year, four values are recommended. Three of these values are based on the average SC-CO_2 from three integrated assessment models (IAMs), at discount rates of 2.5, 3, and 5 percent. In addition, as discussed in the 2010 TSD, there is extensive evidence in the scientific and economic literature on the potential for lower-probability, but higher-impact outcomes from climate change, which would be particularly harmful to society and thus relevant to the public and policymakers. The fourth value is thus included to represent the marginal damages associated with these lower-probability, higher-impact outcomes. Accordingly, this fourth value is selected from further out in the tail of the distribution of SC-CO_2 estimates; specifically, the fourth value corresponds to the 95^{th} percentile of the frequency distribution of SC-CO_2 estimates based on a 3 percent discount rate. Because the present value of economic damages associated with CO_2 emissions change over time, a separate set of estimates is presented for each emissions year through 2050, which is sufficient to cover the time frame addressed in most current regulatory impact analyses.

In May of 2013, the IWG provided an update of the SC-CO_2 estimates based on new versions of each IAM (DICE, PAGE, and FUND). The 2013 update did not revisit other IWG modeling decisions (e.g., the discount rate, reference case socioeconomic and emission scenarios, or equilibrium climate sensitivity). Improvements in the way damages are modeled were confined to those that had been incorporated into the latest versions of the models by the developers themselves in the peer-reviewed literature. The IWG subsequently provided additional minor technical revisions in November of 2013 and July of 2015, as described in Appendix B.

The purpose of this 2016 revision to the TSD is to enhance the presentation and discussion of quantified uncertainty around the current SC-CO_2 estimates, as a response to recommendations in the interim report by the National Academies of Sciences, Engineering, and Medicine. Included herein are an expanded

[1] Throughout this Technical Support Document (TSD) we refer to the estimates as "SC-CO_2 estimates" rather than the more simplified "SCC" abbreviation used in previous versions of the TSD.

graphical presentation of the SC-CO_2 estimates highlighting a symmetric range of uncertainty around estimates for each discount rate, new sections that provide a unified discussion of the methodology used to incorporate sources of uncertainty, and a detailed explanation of the uncertain parameters in both the FUND and PAGE models.

The distributions of SC-CO_2 estimates reflect uncertainty in key model parameters chosen by the IWG such as the sensitivity of the climate to increases in carbon dioxide concentrations, as well as uncertainty in default parameters set by the original model developers. This TSD maintains the same approach to estimating the SC-CO_2 and selecting four values for each emissions year that was used in earlier versions of the TSD. Table ES-1 summarizes the SC-CO_2 estimates for the years 2010 through 2050. These estimates are identical to those reported in the previous version of the TSD, released in July 2015. As explained in previous TSDs, the central value is the average of SC-CO_2 estimates based on the 3 percent discount rate. For purposes of capturing uncertainty around the SC-CO_2 estimates in regulatory impact analysis, the IWG emphasizes the importance of considering all four SC-CO_2 values.

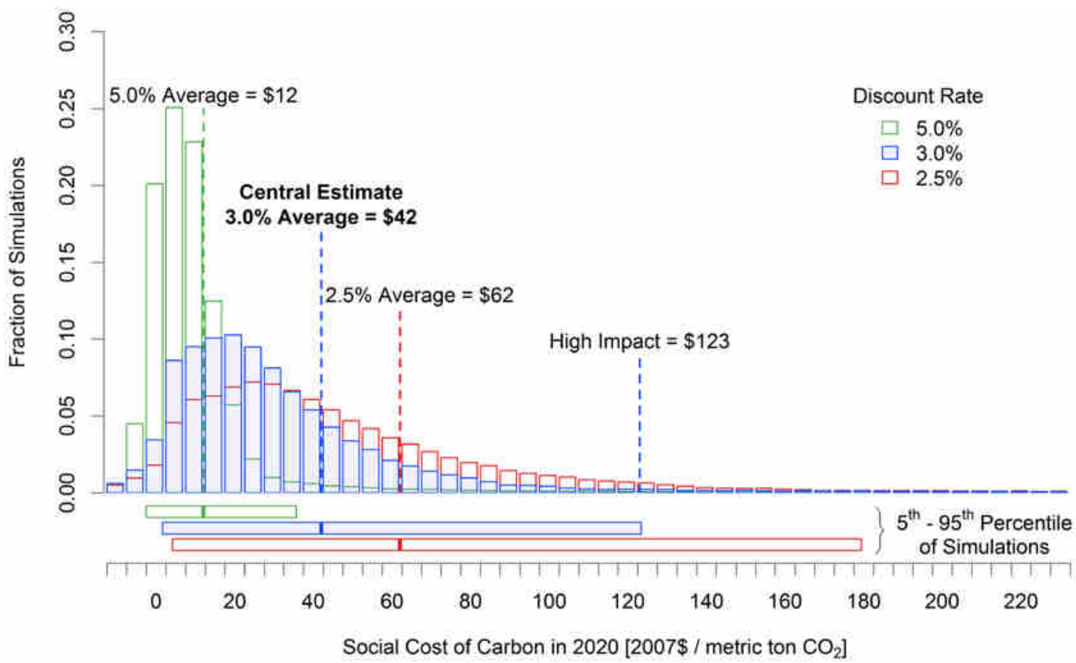
Table ES-1: Social Cost of CO_2, 2010 – 2050 (in 2007 dollars per metric ton of CO_2)

Year	5% Average	**3% Average**	2.5% Average	High Impact (95th Pct at 3%)
2010	10	**31**	50	86
2015	11	**36**	56	105
2020	12	**42**	62	123
2025	14	**46**	68	138
2030	16	**50**	73	152
2035	18	**55**	78	168
2040	21	**60**	84	183
2045	23	**64**	89	197
2050	26	**69**	95	212

While point estimates are important for providing analysts with a tractable approach for regulatory analysis, they do not fully quantify uncertainty associated with the SC-CO_2 estimates. Figure ES-1 presents the quantified sources of uncertainty in the form of frequency distributions for the SC-CO_2 estimates for emissions in 2020. To highlight the difference between the impact of the discount rate on the SC-CO_2 and other quantified sources of uncertainty, the bars below the frequency distributions provide a symmetric representation of quantified variability in the SC-CO_2 estimates for each discount rate. When an agency determines that it is appropriate to conduct additional quantitative uncertainty analysis, it should follow best practices for probabilistic analysis.[2] The full set of information that underlies the frequency distributions in Figure ES-1, which have previously been available upon request, are now available on Office of Management and Budget's (OMB) website for easy public access.

[2] See e.g. OMB Circular A-4, section on *Treatment of Uncertainty*. Available at: https://www.whitehouse.gov/omb/circulars_a004_a-4/#e.

Figure ES-1: Frequency Distribution of SC-CO_2 Estimates for 2020[3]



[3] Although the distributions in Figure ES-1 are based on the full set of model results (150,000 estimates for each discount rate), for display purposes the horizontal axis is truncated with 0.1 to 0.6 percent of the estimates lying below the lowest bin displayed and 0.2 to 3.7 percent of the estimates lying above the highest bin displayed, depending on the discount rate.

I. Purpose

The purpose of this document is to present the current schedule of social cost of carbon ($SC-CO_2$) estimates, along with an enhanced presentation and discussion of quantified sources of uncertainty around the estimates to respond to recommendations in the interim report of the National Academies of Sciences, Engineering, and Medicine (National Academies 2016).[4] Because the last substantive update to the $SC-CO_2$ estimates occurred in May 2013, this document maintains much of the earlier technical discussion from the May 2013 TSD. The $SC-CO_2$ estimates themselves remain unchanged since the July 2015 revision.

E.O. 13563 commits the Administration to regulatory decision making "based on the best available science."[5] Additionally, the IWG recommended in 2010 that the $SC-CO_2$ estimates be revisited on a regular basis or as model updates that reflect the growing body of scientific and economic knowledge become available.[6] By early 2013, new versions of the three integrated assessment models (IAMs) used by the U.S. government to estimate the $SC-CO_2$ (DICE, FUND, and PAGE) were available and had been published in the peer-reviewed literature. While acknowledging the continued limitations of the approach taken by the IWG in 2010 (documented in the original 2010 TSD), the May 2013 TSD provided an update of the $SC-CO_2$ estimates based on the latest peer-reviewed version of the models, replacing model versions that were developed up to ten years earlier in a rapidly evolving field. It did not revisit other assumptions with regard to the discount rate, reference case socioeconomic and emission scenarios, or equilibrium climate sensitivity. Improvements in the way damages are modeled were confined to those that had been incorporated into the latest versions of the models by the developers themselves in the peer-reviewed literature. The agencies participating in the IWG continue to investigate potential improvements to the way in which economic damages associated with changes in CO_2 emissions are quantified.

Section II summarizes the major features of the IAMs used in this TSD that were updated in 2013 relative to the versions of the models used in the 2010 TSD. Section III presents the $SC-CO_2$ estimates for 2010 – 2050 based on these versions of the models. Section IV discusses the treatment of uncertainty in the analysis. Section V provides a discussion of other model limitations and research gaps.

II. Summary of Model Updates

This section briefly reviews the features of the three IAMs used in this TSD (DICE 2010, FUND 3.8, and PAGE 2009) that were updated by the model developers relative to the versions of the models used by the IWG in 2010 (DICE 2007, FUND 3.5, and PAGE 2002). The focus here is on describing those model updates that are relevant to estimating the social cost of carbon, as summarized in Table 1. For example, both the DICE and PAGE models now include an explicit representation of sea level rise damages. Other

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[4] In this document, we present all social cost estimates per metric ton of CO_2 emissions. Alternatively, one could report the social cost per metric ton of carbon emissions. The multiplier for translating between mass of CO_2 and the mass of carbon is 3.67 (the molecular weight of CO_2 divided by the molecular weight of carbon = 44/12 = 3.67).
[5] http://www.whitehouse.gov/sites/default/files/omb/inforeg/eo12866/eo13563_01182011.pdf
[6] See p. 1, 3, 4, 29, and 33 (Interagency Working Group on Social Cost of Carbon 2010).

revisions to PAGE include: updated adaptation assumptions, revisions to ensure damages are constrained by GDP, updated regional scaling of damages, and a revised treatment of potentially abrupt shifts in climate damages. The DICE model's simple carbon cycle has been updated to be more consistent with a more complex climate model. The FUND model includes updated damage functions for sea level rise impacts, the agricultural sector, and reduced space heating requirements, as well as changes to the transient response of temperature to the buildup of GHG concentrations and the inclusion of indirect effects of methane emissions. Changes made to parts of the models that are superseded by the IWG's modeling assumptions—regarding equilibrium climate sensitivity, discounting, and socioeconomic variables—are not discussed here but can be found in the references provided in each section below.

Table 1: Summary of Key Model Revisions Relevant to the IWG SC-CO_2 Estimates

IAM	Version used in 2010 IWG Analysis	Version Used since May 2013	Key changes relevant to IWG SC-CO_2
DICE	2007	2010	Updated calibration of the carbon cycle model and explicit representation of sea level rise (SLR) and associated damages.
FUND	3.5 (2009)	3.8 (2012)	Updated damage functions for space heating, SLR, agricultural impacts, changes to transient response of temperature to buildup of GHG concentrations, and inclusion of indirect climate effects of methane.
PAGE	2002	2009	Explicit representation of SLR damages, revisions to damage function to ensure damages do not exceed 100% of GDP, change in regional scaling of damages, revised treatment of potential abrupt damages, and updated adaptation assumptions.

A. DICE

DICE 2010 includes a number of changes over the previous 2007 version used in the 2010 TSD. The model changes that are relevant for the SC-CO_2 estimates developed by the IWG include: 1) updated parameter values for the carbon cycle model, 2) an explicit representation of sea level dynamics, and 3) a re-calibrated damage function that includes an explicit representation of economic damages from sea level rise. Changes were also made to other parts of the DICE model—including the equilibrium climate sensitivity parameter, the rate of change of total factor productivity, and the elasticity of the marginal utility of consumption—but these components of DICE are superseded by the IWG's assumptions and so will not be discussed here. More details on DICE2007 can be found in Nordhaus (2008) and on DICE2010 in Nordhaus (2010). The DICE2010 model and documentation is also available for download from the homepage of William Nordhaus.

Carbon Cycle Parameters

DICE uses a three-box model of carbon stocks and flows to represent the accumulation and transfer of carbon among the atmosphere, the shallow ocean and terrestrial biosphere, and the deep ocean. These parameters are "calibrated to match the carbon cycle in the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC)" (Nordhaus 2008, p. 44).[7] Carbon cycle transfer coefficient values in DICE2010 are based on re-calibration of the model to match the newer 2009 version of MAGICC (Nordhaus 2010, p. 2). For example, in DICE2010, in each decade 12 percent of the carbon in the atmosphere is transferred to the shallow ocean, 4.7 percent of the carbon in the shallow ocean is transferred to the atmosphere, 94.8 percent remains in the shallow ocean, and 0.5 percent is transferred to the deep ocean. For comparison, in DICE 2007, 18.9 percent of the carbon in the atmosphere is transferred to the shallow ocean each decade, 9.7 percent of the carbon in the shallow ocean is transferred to the atmosphere, 85.3 percent remains in the shallow ocean, and 5 percent is transferred to the deep ocean.

The implication of these changes for DICE2010 is in general a weakening of the ocean as a carbon sink and therefore a higher concentration of carbon in the atmosphere than in DICE2007 for a given path of emissions. All else equal, these changes will generally increase the level of warming and therefore the SC-CO_2 estimates in DICE2010 relative to those from DICE2007.

Sea Level Dynamics

A new feature of DICE2010 is an explicit representation of the dynamics of the global average sea level anomaly to be used in the updated damage function (discussed below). This section contains a brief description of the sea level rise (SLR) module; a more detailed description can be found on the model developer's website.[8] The average global sea level anomaly is modeled as the sum of four terms that represent contributions from: 1) thermal expansion of the oceans, 2) melting of glaciers and small ice caps, 3) melting of the Greenland ice sheet, and 4) melting of the Antarctic ice sheet.

The parameters of the four components of the SLR module are calibrated to match consensus results from the IPCC's Fourth Assessment Report (AR4).[9] The rise in sea level from thermal expansion in each time period (decade) is 2 percent of the difference between the sea level in the previous period and the long run equilibrium sea level, which is 0.5 meters per degree Celsius (°C) above the average global temperature in 1900. The rise in sea level from the melting of glaciers and small ice caps occurs at a rate of 0.008 meters per decade per °C above the average global temperature in 1900.

The contribution to sea level rise from melting of the Greenland ice sheet is more complex. The equilibrium contribution to SLR is 0 meters for temperature anomalies less than 1 °C and increases linearly from 0 meters to a maximum of 7.3 meters for temperature anomalies between 1 °C and 3.5 °C. The contribution to SLR in each period is proportional to the difference between the previous period's sea

[7] MAGICC is a simple climate model initially developed by the U.S. National Center for Atmospheric Research that has been used heavily by the Intergovernmental Panel on Climate Change (IPCC) to emulate projections from more sophisticated state of the art earth system simulation models (Randall et al. 2007).
[8] Documentation on the new sea level rise module of DICE is available on William Nordhaus' website at: http://nordhaus.econ.yale.edu/documents/SLR_021910.pdf.
[9] For a review of post-IPCC AR4 research on sea level rise, see Nicholls et al. (2011) and NAS (2011).

level anomaly and the equilibrium sea level anomaly, where the constant of proportionality increases with the temperature anomaly in the current period.

The contribution to SLR from the melting of the Antarctic ice sheet is -0.001 meters per decade when the temperature anomaly is below 3 °C and increases linearly between 3 °C and 6 °C to a maximum rate of 0.025 meters per decade at a temperature anomaly of 6 °C.

Re-calibrated Damage Function

Economic damages from climate change in the DICE model are represented by a fractional loss of gross economic output in each period. A portion of the remaining economic output in each period (net of climate change damages) is consumed and the remainder is invested in the physical capital stock to support future economic production, so each period's climate damages will reduce consumption in that period and in all future periods due to the lost investment. The fraction of output in each period that is lost due to climate change impacts is represented as a sigmoid, or "S"-shaped, function of the temperature anomaly in the period.[10] The loss function in DICE2010 has been expanded by including a quadratic sub-function of SLR. In DICE2010 the temperature anomaly coefficients have been recalibrated to avoid double-counting damages from sea level rise that were implicitly included in these parameters in DICE2007.

The aggregate damages in DICE2010 are illustrated by Nordhaus (2010, p. 3), who notes that "…damages in the uncontrolled (baseline) [i.e., reference] case … in 2095 are $12 trillion, or 2.8 percent of global output, for a global temperature increase of 3.4 °C above 1900 levels." This compares to a loss of 3.2 percent of global output at 3.4 °C in DICE2007. However, in DICE2010, annual damages are lower in most of the early periods of the modeling horizon but higher in later periods than would be calculated using the DICE2007 damage function. Specifically, the percent difference between damages in the base run of DICE2010 and those that would be calculated using the DICE2007 damage function starts at +7 percent in 2005, decreases to a low of -14 percent in 2065, then continuously increases to +20 percent by 2300 (the end of the IWG analysis time horizon), and to +160 percent by the end of the model time horizon in 2595. The large increases in the far future years of the time horizon are due to the permanence associated with damages from sea level rise, along with the assumption that the sea level is projected to continue to rise long after the global average temperature begins to decrease. The changes to the loss function generally decrease the IWG SC-CO_2 estimates slightly given that relative increases in damages in later periods are discounted more heavily, all else equal.

B. FUND

FUND version 3.8 includes a number of changes over the previous version 3.5 (Narita et al. 2010) used in the 2010 TSD. Documentation supporting FUND and the model's source code for all versions of the model

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[10] The model and documentation, including formulas, are available on the author's webpage at http://www.econ.yale.edu/~nordhaus/homepage/RICEmodels.htm.

is available from the model authors.[11] Notable changes, due to their impact on the SC-CO_2 estimates, are adjustments to the space heating, agriculture, and sea level rise damage functions in addition to changes to the temperature response function and the inclusion of indirect effects from methane emissions.[12] Each of these is discussed in turn.

Space Heating

In FUND, the damages associated with the change in energy needs for space heating are based on the estimated impact due to one degree of warming. These baseline damages are scaled based on the forecasted temperature anomaly's deviation from the one degree benchmark and adjusted for changes in vulnerability due to economic and energy efficiency growth. In FUND 3.5, the function that scales the base year damages adjusted for vulnerability allows for the possibility that in some simulations the benefits associated with reduced heating needs may be an unbounded convex function of the temperature anomaly. In FUND 3.8, the form of the scaling has been modified to ensure that the function is everywhere concave and that there will exist an upper bound on the benefits a region may receive from reduced space heating needs. The new formulation approaches a value of two in the limit of large temperature anomalies, or in other words, assuming no decrease in vulnerability, the reduced expenditures on space heating at any level of warming will not exceed two times the reductions experienced at one degree of warming. Since the reduced need for space heating represents a benefit of climate change in the model, or a negative damage, this change will increase the estimated SC-CO_2. This update accounts for a significant portion of the difference in the expected SC-CO_2 estimates reported by the two versions of the model when run probabilistically.

Sea Level Rise and Land Loss

The FUND model explicitly includes damages associated with the inundation of dry land due to sea level rise. The amount of land lost within a region depends on the proportion of the coastline being protected by adequate sea walls and the amount of sea level rise. In FUND 3.5 the function defining the potential land lost in a given year due to sea level rise is linear in the rate of sea level rise for that year. This assumption implicitly assumes that all regions are well represented by a homogeneous coastline in length and a constant uniform slope moving inland. In FUND 3.8 the function defining the potential land lost has been changed to be a convex function of sea level rise, thereby assuming that the slope of the shore line

[11] http://www.fund-model.org/. This report uses version 3.8 of the FUND model, which represents a modest update to the most recent version of the model to appear in the literature (version 3.7) (Anthoff and Tol, 2013a, 2013b). For the purpose of computing the SC-CO_2, the relevant changes (between 3.7 to 3.8) are associated with improving consistency with IPCC AR4 by adjusting the atmospheric lifetimes of CH_4 and N_2O and incorporating the indirect forcing effects of CH_4, along with making minor stability improvements in the sea wall construction algorithm.
[12] The other damage sectors (water resources, space cooling, land loss, migration, ecosystems, human health, and extreme weather) were not significantly updated.

increases moving inland. The effect of this change is to typically reduce the vulnerability of some regions to sea level rise based land loss, thereby lowering the expected SC-CO_2 estimate. [13]

[13] For stability purposes this report also uses an update to the model which assumes that regional coastal protection measures will be built to protect the most valuable land first, such that the marginal benefits of coastal protection is decreasing in the level of protection following Fankhauser (1995).

Agriculture

In FUND, the damages associated with the agricultural sector are measured as proportional to the sector's value. The fraction is bounded from above by one and is made up of three additive components that represent the effects from carbon fertilization, the rate of temperature change, and the level of the temperature anomaly. In both FUND 3.5 and FUND 3.8, the fraction of the sector's value lost due to the level of the temperature anomaly is modeled as a quadratic function with an intercept of zero. In FUND 3.5, the coefficients of this loss function are modeled as the ratio of two random normal variables. This specification had the potential for unintended extreme behavior as draws from the parameter in the denominator approached zero or went negative. In FUND 3.8, the coefficients are drawn directly from truncated normal distributions so that they remain in the range $[0,\infty)$ and $(-\infty,0]$, respectively, ensuring the correct sign and eliminating the potential for divide-by-zero errors. The means for the new distributions are set equal to the ratio of the means from the normal distributions used in the previous version. In general the impact of this change has been to decrease the range of the distribution while spreading out the distributions' mass over the remaining range relative to the previous version. The net effect of this change on the SC-CO_2 estimates is difficult to predict.

Transient Temperature Response

The temperature response model translates changes in global levels of radiative forcing into the current expected temperature anomaly. In FUND, a given year's increase in the temperature anomaly is based on a mean reverting function where the mean equals the equilibrium temperature anomaly that would eventually be reached if that year's level of radiative forcing were sustained. The rate of mean reversion defines the rate at which the transient temperature approaches the equilibrium. In FUND 3.5, the rate of temperature response is defined as a decreasing linear function of equilibrium climate sensitivity to capture the fact that the progressive heat uptake of the deep ocean causes the rate to slow at higher values of the equilibrium climate sensitivity. In FUND 3.8, the rate of temperature response has been updated to a quadratic function of the equilibrium climate sensitivity. This change reduces the sensitivity of the rate of temperature response to the level of the equilibrium climate sensitivity, a relationship first noted by Hansen et al. (1985) based on the heat uptake of the deep ocean. Therefore in FUND 3.8, the temperature response will typically be faster than in the previous version. The overall effect of this change is likely to increase estimates of the SC-CO_2 as higher temperatures are reached during the timeframe analyzed and as the same damages experienced in the previous version of the model are now experienced earlier and therefore discounted less.

Methane

The IPCC AR4 notes a series of indirect effects of methane emissions, and has developed methods for proxying such effects when computing the global warming potential of methane (Forster et al. 2007). FUND 3.8 now includes the same methods for incorporating the indirect effects of methane emissions. Specifically, the average atmospheric lifetime of methane has been set to 12 years to account for the feedback of methane emissions on its own lifetime. The radiative forcing associated with atmospheric methane has also been increased by 40% to account for its net impact on ozone production and stratospheric water vapor. This update to the model is relevant for the SC-CO_2 because most of the damage functions are non-linear functions of the temperature anomaly, which represents the fact that as the climate system becomes more stressed an additional unit of warming will have a greater impact on damages. Accounting for the indirect effects of CH_4 emissions on temperature will therefore move the model further up the damage curves in the baseline, making a marginal change in emissions of CO_2 more impactful. All else equal, the effect of this increased radiative forcing will be to increase the estimated SC-CO_2 values, due to greater projected temperature anomaly.

C. PAGE

PAGE09 (Hope 2013) includes a number of changes from PAGE2002, the version used in the 2010 TSD. The changes that most directly affect the SC-CO_2 estimates include: explicitly modeling the impacts from sea level rise, revisions to the damage function to ensure damages are constrained by GDP, a change in the regional scaling of damages, a revised treatment for the probability of a discontinuity within the damage function, and revised assumptions on adaptation. The model also includes revisions to the carbon cycle feedback and the calculation of regional temperatures.[14] More details on PAGE09 can be found in Hope (2011a, 2011b, 2011c). A description of PAGE2002 can be found in Hope (2006).

Sea Level Rise

While PAGE2002 aggregates all damages into two categories—economic and non-economic impacts—PAGE09 adds a third explicit category: damages from sea level rise. In the previous version of the model, damages from sea level rise were subsumed by the other damage categories. In PAGE09 sea level damages increase less than linearly with sea level under the assumption that land, people, and GDP are more concentrated in low-lying shoreline areas. Damages from the economic and non-economic sectors were adjusted to account for the introduction of this new category.

Revised Damage Function to Account for Saturation

In PAGE09, small initial economic and non-economic benefits (negative damages) are modeled for small temperature increases, but all regions eventually experience economic damages from climate change, where damages are the sum of additively separable polynomial functions of temperature and sea level rise. Damages transition from this polynomial function to a logistic path once they exceed a certain proportion of remaining Gross Domestic Product (GDP) to ensure that damages do not exceed 100 percent of GDP. This differs from PAGE2002, which allowed Eastern Europe to potentially experience large benefits from temperature increases, and which also did not bound the possible damages that could be experienced.

[14] Because several changes in the PAGE model are structural (e.g., the addition of sea level rise and treatment of discontinuity), it is not possible to assess the direct impact of each change on the SC-CO_2 in isolation as done for the other two models above.

Regional Scaling Factors

As in the previous version of PAGE, the PAGE09 model calculates the damages for the European Union (EU) and then, assumes that damages for other regions are proportional based on a given scaling factor. The scaling factors in PAGE09 are based on the length of each region's coastline relative to the EU (Hope 2011b). Because of the long coastline in the EU, other regions are, on average, less vulnerable than the EU for the same sea level and temperature increase, but all regions have a positive scaling factor. PAGE2002 based its scaling factors on four studies reported in the IPCC's third assessment report, and allowed for benefits from temperature increases in Eastern Europe, smaller impacts in developed countries, and higher damages in developing countries.

Probability of a Discontinuity

In PAGE2002, the damages associated with a "discontinuity" (nonlinear extreme event) were modeled as an expected value. Specifically, a stochastic probability of a discontinuity was multiplied by the damages associated with a discontinuity to obtain an expected value, and this was added to the economic and non-economic impacts. That is, additional damages from an extreme event, such as extreme melting of the Greenland ice sheet, were multiplied by the probability of the event occurring and added to the damage estimate. In PAGE09, the probability of discontinuity is treated as a discrete event for each year in the model. The damages for each model run are estimated either with or without a discontinuity occurring, rather than as an expected value. A large-scale discontinuity becomes possible when the temperature rises beyond some threshold value between 2 and 4°C. The probability that a discontinuity will occur beyond this threshold then increases by between 10 and 30 percent for every 1°C rise in temperature beyond the threshold. If a discontinuity occurs, the EU loses an additional 5 to 25 percent of its GDP (drawn from a triangular distribution with a mean of 15 percent) in addition to other damages, and other regions lose an amount determined by their regional scaling factor. The threshold value for a possible discontinuity is lower than in PAGE2002, while the rate at which the probability of a discontinuity increases with the temperature anomaly and the damages that result from a discontinuity are both higher than in PAGE2002. The model assumes that only one discontinuity can occur and that the impact is phased in over a period of time, but once it occurs, its effect is permanent.

Adaptation

As in PAGE2002, adaptation is available to help mitigate any climate change impacts that occur. In PAGE this adaptation is the same regardless of the temperature change or sea level rise and is therefore akin to what is more commonly considered a reduction in vulnerability. It is modeled by reducing the damages by some percentage. PAGE09 assumes a smaller decrease in vulnerability than the previous version of the model and assumes that it will take longer for this change in vulnerability to be realized. In the aggregated economic sector, at the time of full implementation, this adaptation will mitigate all damages up to a temperature increase of 1°C, and for temperature anomalies between 1°C and 2°C, it will reduce damages by 15-30 percent (depending on the region). However, it takes 20 years to fully implement this adaptation. In PAGE2002, adaptation was assumed to reduce economic sector damages up to 2°C by 50-90 percent after 20 years. Beyond 2°C, no adaptation is assumed to be available to mitigate the impacts of climate change. For the non-economic sector, in PAGE09 adaptation is available to reduce 15 percent of the damages due to a temperature increase between 0°C and 2°C and is assumed to take 40 years to fully implement, instead of 25 percent of the damages over 20 years assumed in PAGE2002. Similarly, adaptation is assumed to alleviate 25-50 percent of the damages from the first 0.20 to 0.25 meters of sea level rise but is assumed to be ineffective thereafter. Hope (2011c) estimates that the less optimistic assumptions regarding the ability to offset impacts of temperature and sea level rise via adaptation increase the SC-CO_2 by approximately 30 percent.

Other Noteworthy Changes

Two other changes in the model are worth noting. There is a change in the way the model accounts for decreased CO_2 absorption on land and in the ocean as temperature rises. PAGE09 introduces a linear feedback from global mean temperature to the percentage gain in the excess concentration of CO_2, capped at a maximum level. In PAGE2002, an additional amount was added to the CO_2 emissions each period to account for a decrease in ocean absorption and a loss of soil carbon. Also updated is the method by which the average global and annual temperature anomaly is downscaled to determine annual average regional temperature anomalies to be used in the regional damage functions. In PAGE2002, the scaling was determined solely based on regional difference in emissions of sulfate aerosols. In PAGE09, this regional temperature anomaly is further adjusted using an additive factor that is based on the average absolute latitude of a region relative to the area weighted average absolute latitude of the Earth's landmass, to capture relatively greater changes in temperature forecast to be experienced at higher latitudes.

III. SC-CO_2 Estimates

The three IAMs were run using the same methodology detailed in the 2010 TSD (Interagency Working Group on Social Cost of Carbon 2010). The approach, along with the inputs for the socioeconomic emissions scenarios, equilibrium climate sensitivity distribution, and discount rate remains the same. This includes the five reference scenarios based on the EMF-22 modeling exercise, the Roe and Baker equilibrium climate sensitivity distribution calibrated to the IPCC AR4, and three constant discount rates of 2.5, 3, and 5 percent.

As was previously the case, use of three models, three discount rates, and five scenarios produces 45 separate frequency distributions of SC-CO_2 estimates in a given year. The approach laid out in the 2010 TSD applied equal weight to each model and socioeconomic scenario in order to reduce the dimensionality down to three separate distributions, one for each of the three discount rates. The IWG selected four values from these distributions for use in regulatory analysis. Three values are based on the average SC-CO_2 across models and socioeconomic and emissions scenarios at the 2.5, 3, and 5 percent discount rates, respectively. The fourth value is included to provide information on the marginal damages associated with lower-probability, higher-impact outcomes that would be particularly harmful to society. As discussed in the 2010 TSD, there is extensive evidence in the scientific and economic literature of the potential for lower-probability, higher-impact outcomes from climate change, which would be particularly harmful to society and thus relevant to the public and policymakers. This points to the relevance of values above the mean in right skewed distributions. Accordingly, this fourth value is selected from further out in the tails of the frequency distribution of SC-CO_2 estimates, and, in particular, is set to the 95th percentile of the frequency distribution of SC-CO_2 estimates based on a 3 percent discount rate. (A detailed set of percentiles by model and scenario combination and additional summary statistics for the 2020 values is available in Appendix A.) As noted in the 2010 TSD, "the 3 percent discount rate is the central value, and so the central value that emerges is the average SC-CO_2 across models at the 3 percent discount rate" (Interagency Working Group on Social Cost of Carbon 2010, p. 25). However, for purposes of capturing the uncertainties involved in regulatory impact analysis, the IWG emphasizes the importance and value of including all four SC-CO_2 values.

Table 2 shows the four selected SC-CO_2 estimates in five year increments from 2010 to 2050. Values for 2010, 2020, 2030, 2040, and 2050 are calculated by first combining all outputs (10,000 estimates per model run) from all scenarios and models for a given discount rate. Values for the years in between are calculated using linear interpolation. The full set of revised annual SC-CO_2 estimates between 2010 and 2050 is reported in the Appendix and the full set of model results are available on the OMB website.[15]

Table 2: Social Cost of CO_2, 2010 – 2050 (in 2007 dollars per metric ton of CO_2)

Year	5% Average	**3% Average**	2.5% Average	High Impact (95th Pct at 3%)
2010	10	**31**	50	86
2015	11	**36**	56	105
2020	12	**42**	62	123
2025	14	**46**	68	138
2030	16	**50**	73	152
2035	18	**55**	78	168
2040	21	**60**	84	183
2045	23	**64**	89	197
2050	26	**69**	95	212

As was the case in the 2010 TSD, the SC-CO_2 increases over time because future emissions are expected to produce larger incremental damages as physical and economic systems become more stressed in response to greater climatic change, and because GDP is growing over time and many damage categories are modeled as proportional to gross GDP. The approach taken by the IWG is to compute the cost of a marginal ton emitted in the future by running the models for a set of perturbation years out to 2050. Table 3 illustrates how the growth rate for these four SC-CO_2 estimates varies over time.

[15] https://www.whitehouse.gov/omb/oira/social-cost-of-carbon.

Table 3: Average Annual Growth Rates of $SC\text{-}CO_2$ Estimates between 2010 and 2050

Average Annual Growth Rate (%)	5.0% Avg	3.0% Avg	2.5% Avg	3.0% 95th
2010-2020	1.2%	3.2%	2.4%	4.4%
2020-2030	3.4%	2.1%	1.7%	2.3%
2030-2040	3.0%	1.9%	1.5%	2.0%
2040-2050	2.6%	1.6%	1.3%	1.6%

The future monetized value of emission reductions in each year (the $SC\text{-}CO_2$ in year *t* multiplied by the change in emissions in year *t*) must be discounted to the present to determine its total net present value for use in regulatory analysis. As previously discussed in the 2010 TSD, damages from future emissions should be discounted at the same rate as that used to calculate the $SC\text{-}CO_2$ estimates themselves to ensure internal consistency—i.e., future damages from climate change, whether they result from emissions today or emissions in a later year, should be discounted to the base year of the analysis using the same rate.

Current guidance contained in OMB Circular A-4 indicates that analysis of economically significant proposed and final regulations from the domestic perspective is required, while analysis from the international perspective is optional. However, the IWG (including OMB) determined that a modified approach is more appropriate in this case because the climate change problem is highly unusual in a number of respects. First, it involves a global externality: emissions of most greenhouse gases contribute to damages around the world even when they are emitted in the United States—and conversely, greenhouse gases emitted elsewhere contribute to damages in the United States. Consequently, to address the global nature of the problem, the $SC\text{-}CO_2$ must incorporate the full (global) damages caused by GHG emissions. Second, climate change presents a problem that the United States alone cannot solve. Other countries will also need to take action to reduce emissions if significant changes in the global climate are to be avoided. Emphasizing the need for a global solution to a global problem, the United States has been actively involved in seeking international agreements to reduce emissions. For example, the United States joined over 170 other nations and signed the Paris Agreement on April 22, 2016, signaling worldwide commitment to reduce GHG emissions. The United States has been active in encouraging other nations, including emerging major economies, to take significant steps to reduce emissions. Using a global estimate of damages in U.S. regulatory analyses sends a strong signal to other nations that they too should base their emissions reductions strategies on a global perspective, thus supporting a cooperative and mutually beneficial approach to achieving needed reduction. Thirteen prominent academics noted that these "are compelling reasons to focus on a global [$SC\text{-}CO_2$]" in a recent article on the $SC\text{-}CO_2$ (Pizer et al. 2014). In addition, adverse impacts on other countries can have spillover effects on the United States, particularly in the areas of national security, international trade, public health, and humanitarian concerns. When these considerations are taken as a whole, the IWG concluded that a global measure of the benefits from reducing U.S. emissions is appropriate. For additional discussion, see the 2010 TSD.

IV. Treatment of Uncertainty

Uncertainty about the value of the SC-CO_2 is in part inherent, as with any analysis that looks into the future, but it is also driven by current data gaps associated with the complex physical, economic, and behavioral processes that link GHG emissions to human health and well-being. Some sources of uncertainty pertain to aspects of the natural world, such as quantifying the physical effects of greenhouse gas emissions on Earth systems. Other sources of uncertainty are associated with current and future human behavior and well-being, such as population and economic growth, GHG emissions, the translation of Earth system changes to economic damages, and the role of adaptation. It is important to note that even in the presence of uncertainty, scientific and economic analysis can provide valuable information to the public and decision makers, though the uncertainty should be acknowledged and when possible taken into account in the analysis. This section summarizes the sources of uncertainty that the IWG was able to consider in a quantitative manner in estimating the SC-CO_2. Further discussion on sources of uncertainty that are active areas of research and have not yet been fully quantified in the SC-CO_2 estimates is provided in Section V and in the 2010 TSD.

In developing the SC-CO_2 estimates, the IWG considered various sources of uncertainty through a combination of a multi-model ensemble, probabilistic analysis, and scenario analysis. For example, the three IAMs used collectively span a wide range of Earth system and economic outcomes to help reflect the uncertainty in the literature and in the underlying dynamics being modeled. The use of an ensemble of three different models is also intended to, at least partially, address the fact that no single model includes all of the quantified economic damages. It also helps to reflect structural uncertainty across the models, which is uncertainty in the underlying relationships between GHG emissions, Earth systems, and economic damages that are included in the models. Bearing in mind the different limitations of each model (discussed in the 2010 TSD) and lacking an objective basis upon which to differentially weight the models, the three IAMs are given equal weight in the analysis.

The IWG used Monte Carlo techniques to run the IAMs a large number of times. In each simulation the uncertain parameters are represented by random draws from their defined probability distributions. In all three models the equilibrium climate sensitivity is treated probabilistically based on the probability distribution described in the 2010 TSD. The equilibrium climate sensitivity is a key parameter in this analysis because it helps define the strength of the climate response to increasing GHG concentrations in the atmosphere. In addition, the FUND and PAGE models define many of their parameters with probability distributions instead of point estimates. For these two models, the model developers' default probability distributions are maintained for all parameters other than those superseded by the IWG's harmonized inputs (i.e., equilibrium climate sensitivity, socioeconomic and emissions scenarios, and discount rates). More information on the uncertain parameters in PAGE and FUND is presented in Appendix C.

For the socioeconomic and emissions scenarios, uncertainty is included in the analysis by considering a range of scenarios, which are described in detail in the 2010 SC-CO_2 TSD. As noted in the 2010 TSD, while the IWG considered formally assigning probability weights to the different socioeconomic scenarios selected, it came to the conclusion that this could not be accomplished in an analytically rigorous way given the dearth of information on the likelihood of a full range of future socioeconomic pathways. Thus, the IWG determined that, because no basis for assigning differential weights was available, the most transparent way to present a range of uncertainty was simply to weight each of the five scenarios equally for the consolidated estimates. To provide additional information as to how the results vary with the scenarios, summarized results for each scenario are presented separately in Appendix A. The results of each model run are available on the OMB website.

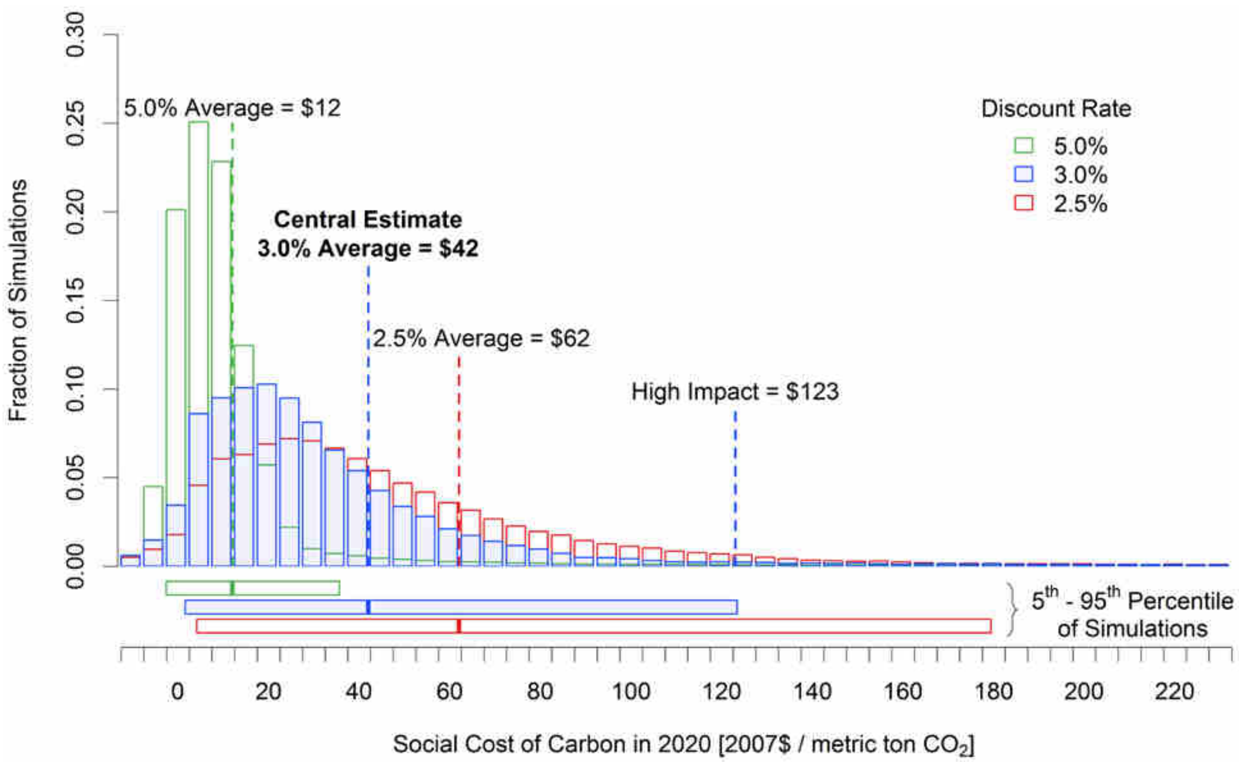
Finally, based on the review of the literature, the IWG chose discount rates that reflect reasonable judgements under both prescriptive and descriptive approaches to intergenerational discounting. As discussed in the 2010 TSD, in light of disagreement in the literature on the appropriate discount rate to use in this context and uncertainty about how rates may change over time, the IWG selected three certainty-equivalent constant discount rates to span a plausible range: 2.5, 3, and 5 percent per year. However, unlike the approach taken for consolidating results across models and socioeconomic and emissions scenarios, the SC-CO_2 estimates are not pooled across different discount rates because the range of discount rates reflects both uncertainty and, at least in part, different policy or value judgements.

The outcome of accounting for various sources of uncertainty using the approaches described above is a frequency distribution of the SC-CO_2 estimates for emissions occurring in a given year for each of the three discount rates. These frequency distributions reflect the uncertainty around the input parameters for which probability distributions were defined, as well as from the multi-model ensemble and socioeconomic and emissions scenarios where probabilities were implied by the equal weighting assumption. It is important to note that the set of SC-CO_2 estimates obtained from this analysis does not yield a probability distribution that fully characterizes uncertainty about the SC-CO_2 due to impact categories omitted from the models and sources of uncertainty that have not been fully characterized due to data limitations.

Figure 1 presents the frequency distribution of the SC-CO_2 estimates for emissions in 2020 for each of the three discount rates. Each of these distributions represents 150,000 estimates based on 10,000 simulations for each combination of the three models and five socioeconomic and emissions scenarios.[16] In general, the distributions are skewed to the right and have long right tails, which tend to be even longer for lower discount rates. To highlight the difference between the impact of the discount rate on the SC-CO_2 and other quantified sources of uncertainty, the bars below the frequency distributions provide a symmetric representation of quantified variability in the SC-CO_2 estimates conditioned on each discount rate. The full set of SC-CO_2 results through 2050 is available on OMB's website. This may be useful to analysts in situations that warrant additional quantitative uncertainty analysis (e.g., as recommended by OMB for rules that exceed $1 billion in annual benefits or costs). See OMB Circular A-4 for guidance and discussion of best practices in conducting uncertainty analysis in RIAs.

[16] Although the distributions in Figure 1 are based on the full set of model results (150,000 estimates for each discount rate), for display purposes the horizontal axis is truncated with 0.1 to 0.6 percent of the estimates lying below the lowest bin displayed and 0.2 to 3.7 percent of the estimates lying above the highest bin displayed, depending on the discount rate.

Figure 1: Frequency Distribution of SC-CO_2 Estimates for 2020 (in 2007$ per metric ton CO_2)



As previously described, the SC-CO_2 estimates produced by the IWG are based on a rigorous approach to accounting for quantifiable uncertainty using multiple analytical techniques. In addition, the scientific and economics literature has further explored known sources of uncertainty related to estimates of the SC-CO_2. For example, researchers have published papers that explore the sensitivity of IAMs and the resulting SC-CO_2 estimates to different assumptions embedded in the models (see, e.g., Hope (2013), Anthoff and Tol (2013a), and Nordhaus (2014)). However, there remain additional sources of uncertainty that have not been fully characterized and explored due to remaining data limitations. Additional research is needed in order to expand the quantification of various sources of uncertainty in estimates of the SC-CO_2 (e.g., developing explicit probability distributions for more inputs pertaining to climate impacts and their valuation). The IWG is actively following advances in the scientific and economic literature that could provide guidance on, or methodologies for, a more robust incorporation of uncertainty.

V. Other Model Limitations and Research Gaps

The 2010 SC-CO_2 TSD discusses a number of important limitations for which additional research is needed. In particular, the document highlights the need to improve the quantification of both non-catastrophic and catastrophic damages, the treatment of adaptation and technological change, and the way in which inter-regional and inter-sectoral linkages are modeled. While the more recent versions of the models discussed above offer some improvements in these areas, further research is still needed. Currently, IAMs do not include all of the important physical, ecological, and economic impacts of climate change recognized in the climate change literature due to a lack of precise information on the nature of damages and because the science incorporated into these models understandably lags behind the most recent research.[17] These individual limitations do not all work in the same direction in terms of their influence on the SC-CO_2 estimates; however, it is the IWG's judgment that, taken together, these limitations suggest that the SC-CO_2 estimates are likely conservative. In particular, the IPCC Fourth Assessment Report (Meehl et al. 2007), which was the most current IPCC assessment available at the time of the IWG's 2009-2010 review, concluded that SC-CO_2 estimates "very likely…underestimate the damage costs" due to omitted impacts. Since then, the peer-reviewed literature has continued to support this conclusion, as noted in the IPCC Fifth Assessment report (Oppenheimer et al. 2014).

Another area of active research relates to intergenerational discounting, including the application of discount rates to regulations in which some costs and benefits accrue intra-generationally while others accrue inter-generationally. Some experts have argued that a declining discount rate would be appropriate to analyze impacts that occur far into the future (Arrow et al. 2013). However, additional research and analysis is still needed to develop a methodology for implementing a declining discount rate and to understand the implications of applying these theoretical lessons in practice.

The 2010 TSD also discusses the need to more carefully assess the implications of risk aversion for SC-CO_2 estimation as well as the substitution possibilities between climate and non-climate goods at higher temperature increases, both of which have implications for the discount rate used. EPA, DOE, and other agencies continue to engage in research on modeling and valuation of climate impacts that can potentially improve SC-CO_2 estimation in the future. See the 2010 SC-CO_2 TSD for the full discussion.

[17] See, for example, Howard (2014) and EPRI (2014) for recent discussions.

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Appendix A

Table A1: Annual SC-CO_2 Values: 2010-2050 (2007$/metric ton CO_2)

Year	5% Average	**3% Average**	2.5% Average	High Impact (95th Pct at 3%)
2010	10	**31**	50	86
2011	11	**32**	51	90
2012	11	**33**	53	93
2013	11	**34**	54	97
2014	11	**35**	55	101
2015	11	**36**	56	105
2016	11	**38**	57	108
2017	11	**39**	59	112
2018	12	**40**	60	116
2019	12	**41**	61	120
2020	12	**42**	62	123
2021	12	**42**	63	126
2022	13	**43**	64	129
2023	13	**44**	65	132
2024	13	**45**	66	135
2025	14	**46**	68	138
2026	14	**47**	69	141
2027	15	**48**	70	143
2028	15	**49**	71	146
2029	15	**49**	72	149
2030	16	**50**	73	152
2031	16	**51**	74	155
2032	17	**52**	75	158
2033	17	**53**	76	161
2034	18	**54**	77	164
2035	18	**55**	78	168
2036	19	**56**	79	171
2037	19	**57**	81	174
2038	20	**58**	82	177
2039	20	**59**	83	180
2040	21	**60**	84	183
2041	21	**61**	85	186
2042	22	**61**	86	189
2043	22	**62**	87	192
2044	23	**63**	88	194
2045	23	**64**	89	197
2046	24	**65**	90	200
2047	24	**66**	92	203
2048	25	**67**	93	206
2049	25	**68**	94	209
2050	26	**69**	95	212

Table A2: 2020 Global SC-CO_2 Estimates at 2.5 Percent Discount Rate (2007$/metric ton CO_2)

Percentile	1st	5th	10th	25th	50th	Avg	75th	90th	95th	99th
Scenario[18]					PAGE					
IMAGE	6	10	15	26	55	123	133	313	493	949
MERGE Optimistic	4	6	8	15	32	75	79	188	304	621
MESSAGE	4	7	10	19	41	104	103	266	463	879
MiniCAM Base	5	8	12	21	45	102	108	255	412	835
5th Scenario	2	4	6	11	24	81	66	192	371	915
Scenario					DICE					
IMAGE	25	31	37	47	64	72	92	123	139	161
MERGE Optimistic	14	18	20	26	36	40	50	65	74	85
MESSAGE	20	24	28	37	51	58	71	95	109	221
MiniCAM Base	20	25	29	38	53	61	76	102	117	135
5th Scenario	17	22	25	33	45	52	65	91	106	126
Scenario					FUND					
IMAGE	-14	-2	4	15	31	39	55	86	107	157
MERGE Optimistic	-6	1	6	14	27	35	46	70	87	141
MESSAGE	-16	-5	1	11	24	31	43	67	83	126
MiniCAM Base	-7	2	7	16	32	39	55	83	103	158
5th Scenario	-29	-13	-6	4	16	21	32	53	69	103

Table A3: 2020 Global SC-CO_2 Estimates at 3 Percent Discount Rate (2007$/metric ton CO_2)

Percentile	1st	5th	10th	25th	50th	Avg	75th	90th	95th	99th
Scenario					PAGE					
IMAGE	4	7	9	17	36	87	91	228	369	696
MERGE Optimistic	2	4	6	10	22	54	55	136	222	461
MESSAGE	3	5	7	13	28	72	71	188	316	614
MiniCAM Base	3	5	7	13	29	70	72	177	288	597
5th Scenario	1	3	4	7	16	55	46	130	252	632
Scenario					DICE					
IMAGE	16	21	24	32	43	48	60	79	90	102
MERGE Optimistic	10	13	15	19	25	28	35	44	50	58
MESSAGE	14	18	20	26	35	40	49	64	73	83
MiniCAM Base	13	17	20	26	35	39	49	65	73	85
5th Scenario	12	15	17	22	30	34	43	58	67	79
Scenario					FUND					
IMAGE	-13	-4	0	8	18	23	33	51	65	99
MERGE Optimistic	-7	-1	2	8	17	21	29	45	57	95
MESSAGE	-14	-6	-2	5	14	18	26	41	52	82
MiniCAM Base	-7	-1	3	9	19	23	33	50	63	101
5th Scenario	-22	-11	-6	1	8	11	18	31	40	62

[18] See 2010 TSD for a description of these scenarios.

Table A4: 2020 Global SC-CO_2 Estimates at 5 Percent Discount Rate (2007$/metric ton CO_2)

Percentile	1st	5th	10th	25th	50th	Avg	75th	90th	95th	99th
Scenario					PAGE					
IMAGE	1	2	2	4	10	27	26	68	118	234
MERGE Optimistic	1	1	2	3	6	17	17	43	72	146
MESSAGE	1	1	2	4	8	23	22	58	102	207
MiniCAM Base	1	1	2	3	8	20	20	52	90	182
5th Scenario	0	1	1	2	5	17	14	39	75	199
Scenario					DICE					
IMAGE	6	8	9	11	14	15	18	22	25	27
MERGE Optimistic	4	5	6	7	9	10	12	15	16	18
MESSAGE	6	7	8	10	12	13	16	20	22	25
MiniCAM Base	5	6	7	8	11	12	14	18	20	22
5th Scenario	5	6	6	8	10	11	14	17	19	21
Scenario					FUND					
IMAGE	-9	-5	-4	-1	2	3	6	10	14	24
MERGE Optimistic	-6	-4	-2	0	3	4	6	11	15	26
MESSAGE	-10	-6	-4	-1	1	2	5	9	12	21
MiniCAM Base	-7	-4	-2	0	3	4	6	11	14	25
5th Scenario	-11	-7	-5	-3	0	0	3	5	7	13

Table A5: Additional Summary Statistics of 2020 Global SC-CO_2 Estimates

Discount rate:	5.0%				3.0%				2.5%			
Statistic:	Mean	Variance	Skewness	Kurtosis	Mean	Variance	Skewness	Kurtosis	Mean	Variance	Skewness	Kurtosis
DICE	12	26	2	15	38	409	3	24	57	1097	3	30
PAGE	21	1481	5	32	68	13712	4	22	97	26878	4	23
FUND	3	41	5	179	19	1452	-42	8727	33	6154	-73	14931

Appendix B

The November 2013 revision of this TSD is based on two corrections to the runs based on the FUND model. First, the potential dry land loss in the algorithm that estimates regional coastal protections was misspecified in the model's computer code. This correction is covered in an erratum to Anthoff and Tol (2013a) published in the same journal (*Climatic Change*) in October 2013 (Anthoff and Tol (2013b)). Second, the equilibrium climate sensitivity distribution was inadvertently specified as a truncated Gamma distribution (the default in FUND) as opposed to the truncated Roe and Baker distribution as was intended. The truncated Gamma distribution used in the FUND runs had approximately the same mean and upper truncation point, but lower variance and faster decay of the upper tail, as compared to the intended specification based on the Roe and Baker distribution. The difference between the original estimates reported in the May 2013 version of this TSD and this revision are generally one dollar or less.

The July 2015 revision of this TSD is based on two corrections. First, the DICE model had been run up to 2300 rather than through 2300, as was intended, thereby leaving out the marginal damages in the last year of the time horizon. Second, due to an indexing error, the results from the PAGE model were in 2008 U.S. dollars rather than 2007 U.S. dollars, as was intended. In the current revision, all models have been run through 2300, and all estimates are in 2007 U.S. dollars. On average the revised SC-CO_2 estimates are one dollar less than the mean SC-CO_2 estimates reported in the November 2013 version of this TSD. The difference between the 95th percentile estimates with a 3% discount rate is slightly larger, as those estimates are heavily influenced by results from the PAGE model.

The July 2016 revision provides additional discussion of uncertainty in response to recommendations from the National Academy of Sciences, Engineering, and Medicine. It does not revisit the IWG's 2010 methodological decisions or update the schedule of SC-CO_2 estimates presented in the July 2015 revision. The IWG is currently seeking external expert advice from the National Academies on the technical merits and challenges of potential approaches to future updates of the SC-CO_2 estimates presented in this TSD. To date, the Academies' committee has issued an interim report that recommended against a near-term update to the SC-CO_2 estimates, but included recommendations for enhancing the presentation and discussion of uncertainty around the current estimates. This revision includes additional information that the IWG determined was appropriate to respond to these recommendations. Specifically, the executive summary presents more information about the range of quantified uncertainty in the SC-CO_2 estimates (including a graphical representation of symmetric high and low values from the frequency distribution of SC-CO_2 estimates conditional on each discount rate), and a new section has also been added that provides a unified discussion of the various sources of uncertainty and how they were handled in estimating the SC-CO_2. Efforts to make the sources of uncertainty clear have also been enhanced with the addition of a new appendix that describes in more detail the uncertain parameters in both the FUND and PAGE models (Appendix C). Furthermore, the full set of SC-CO_2 modeling results, which have previously been available upon request, are now provided on the OMB website for easy access. The Academies' final report (expected in early 2017) will provide longer term recommendations for a more comprehensive update. For more information on the status of the Academies' process, see: http://sites.nationalacademies.org/DBASSE/BECS/CurrentProjects/DBASSE_167526.

Appendix C

This appendix provides a general overview of the parameters that are treated probabilistically in each of the three integrated assessment models the IWG used to estimate the SC-CO_2. In the DICE model the only uncertain parameter considered was the equilibrium climate sensitivity as defined by the probability distribution harmonized across the three models. By default, all of the other parameters in the model are defined by point estimates and these definitions were maintained by the IWG. In the FUND and PAGE models many of the parameters, beyond the equilibrium climate sensitivity, are defined by probability distributions in the default versions of the models. The IWG maintained these default assumptions and allowed these parameters to vary in the Monte Carlo simulations conducted with the FUND and PAGE models.

Default Uncertainty Assumptions in FUND

In the version of the FUND model used by the IWG (version 3.8.1) over 90 of the over 150 parameters in the model are defined by probability distributions instead of point estimates, and for 30 of those parameters the values vary across the model's 16 regions. This includes parameters related to the physical and economic components of the model. The default assumptions in the model include parameters whose probability distributions are based on the normal, Gamma, and triangular distributions. In most cases the distributions are truncated from above or below. The choice of distributions and parameterizations are based on the model developers' assessment of the scientific and economic literature. Complete information on the exact probability distributions specified for each uncertain parameter is provided through the model's documentation, input data, and source code, available at: http://www.fund-model.org/home.

The physical components of the model map emissions to atmospheric concentrations, then map those concentrations to radiative forcing, which is then mapped to changes in global mean temperature. Changes in temperature are then used to estimate sea level rise. The parameters treated probabilistically in these relationships may be grouped into three main categories: atmospheric lifetimes, speed of temperature response, and sea level rise. First, atmospheric concentrations are determined by one box models, that capture a single representative sink, for each of the three non-CO_2 GHGs and a five box model for CO_2, that represents the multiple sinks in the carbon cycle that operate on different time frames. In each of these boxes, the lifetime of additions to the atmospheric concentration in the box are treated as uncertain. Second, parameters associated with speed at which the climate responds to changes in radiative forcing are treated as uncertain. In the FUND model radiative forcing, R_t, is mapped to changes in global mean temperature, T_t, through

$$T_t = T_{t-1} + \frac{1}{\theta_1 + \theta_2 ECS + \theta_3 ECS^2}\left(\frac{\psi ECS}{\ln(2)} R_t - T_{1-t}\right),$$

where the probability distribution for the equilibrium climate sensitivity, ECS, was harmonized across the models as discussed in the 2010 TSD. The parameters θ_i define the speed at which the temperature anomaly responds to changes in radiative forcing and are treated as uncertain in the model. Third, sea level rise is treated as a mean reverting function, where the mean is determined as proportional to the current global mean temperature anomaly. Both this proportionality parameter and the rate of mean reversion in this relationship are treated as uncertain in the model.

The economic components of the model map changes in the physical components to monetized damages. To place the uncertain parameters of the model associated with mapping physical endpoints to damages in context, it is useful to consider the general form of the damage functions in the model. Many of the damage functions in the model have forms that are roughly comparable to

$$D_{r,t} = \alpha_r Y_{r,t} \beta_{r,t} \left(\frac{y_{r,t}}{y_{r,b}} \right)^{\gamma} \left(\frac{N_{r,t}}{N_{r,b}} \right)^{\phi} T_t^{\delta}, \tag{1}$$

where α_r is the damage at a 1 °C global mean temperature increase as a fraction of regional GDP, $Y_{r,t}$. The model considers numerous changes that may reduce a region's benchmark vulnerability to climate change. For example, γ represents the elasticity of damages with respect to changes in the region's GDP per capita, $y_{r,t}$, relative to a benchmark value, $y_{r,b}$; ϕ represents the elasticity of damages with respect to changes in the region's population, $N_{r,t}$, relative to a benchmark value, $N_{r,b}$; and the projection $\beta_{r,t}$ provides for an exogenous reduction in vulnerability (e.g., forecast energy efficiency improvements the affect space cooling costs). Once the benchmark damages have been scaled due to changes in vulnerability they are adjusted based on a non-linear scaling of the level of climate change forecast, using a power function with the exponent, δ.

Some damage categories have damage function specifications that differ from the example in (1). For example, agriculture and forestry damages take atmospheric concentrations of CO_2 and the rate of climate change into account in different forms, though the method by which they calculate the monetized impact in these cases is similar with respect to accounting for GDP growth and changes in vulnerability. In other cases the process by which damages are estimated is more complex. For example, in estimating damages from sea level rise the model considers explicit regional decision makers that choose levels of coastal protection in a given year based on a benefit-cost test. In estimating the damages from changes in cardiovascular mortality risk the model considers forecast changes in the proportion of the population over the age of 65 and deemed most vulnerable by the model developers. Other damage categories may also have functional forms that differ slightly from (1), but in general this form provides a useful framework for discussing the parameters for which the model developers have defined probability distributions as opposed to point estimates.

In many damage categories (e.g., sea level rise, water resources, biodiversity loss, agriculture and forestry, and space conditioning) the benchmark damages, α_r, are treated as uncertain parameters in the model and in most case they are assumed to vary by region. The elasticity of damages with respect to changes in regional GDP per capita, γ, and the elasticity with respect to changes in regional population, ϕ, are also treated as uncertain parameters in most damage functions in the model, though they are not assumed to vary across regions. In most cases the exponent, δ, on the power function that scales damages based on the forecast level of climate change are also treated as uncertain parameters, though they are not assumed to vary across regions in most cases.

Figure C1 presents results of an analysis from the developers of the FUND model that examines the uncertain parameters that have the greatest influence on estimates of the SC-CO_2 based on the default version of the model. While some of the modeling inputs are different for the SC-CO_2 estimates calculated by the IWG these parameters are likely to remain highly influential in the FUND modeling results.

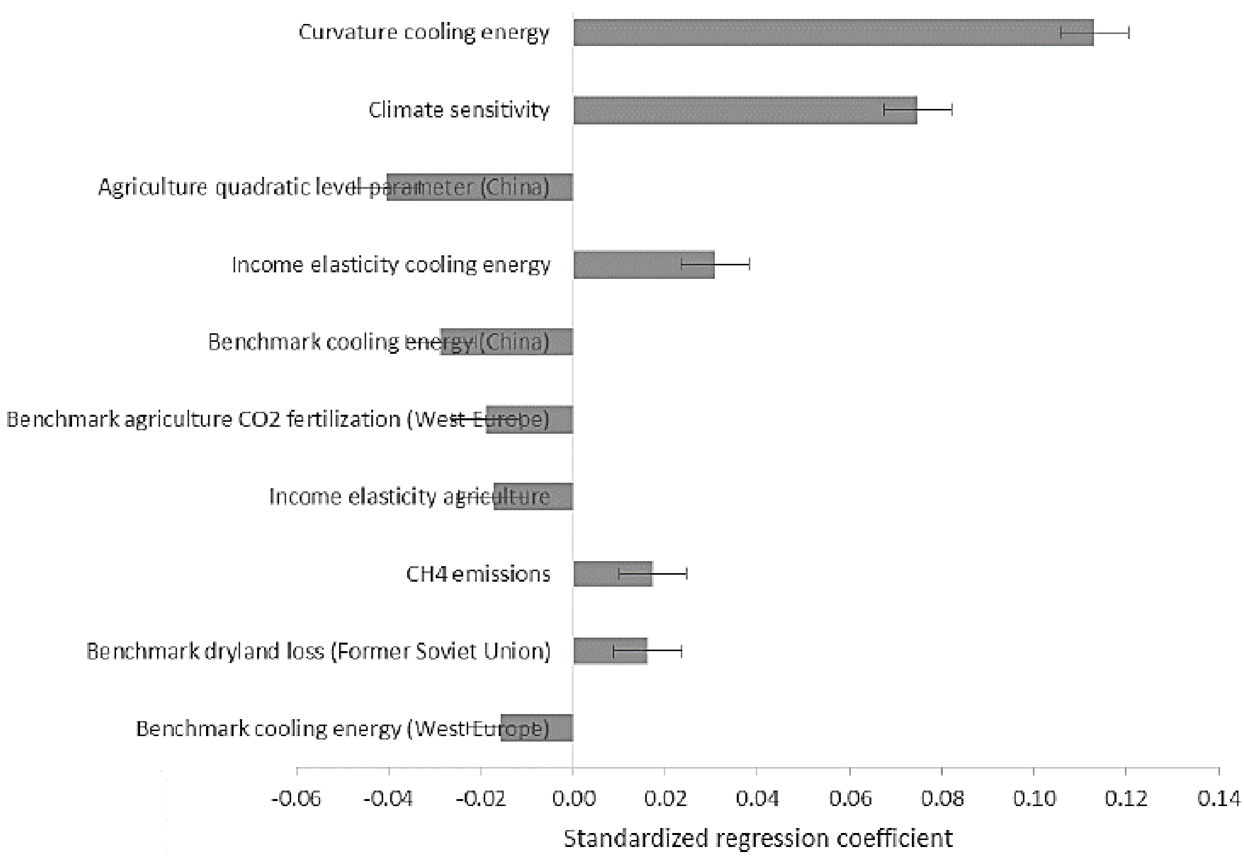

Figure C1: Influence of Key Uncertain Parameters in Default FUND Model (Anthoff and Tol 2013a)[19]

Default Uncertainty Assumptions in PAGE

In the version of the PAGE model used by the IWG (version PAGE09) there are over 40 parameters defined by probability distributions instead of point estimates.[20] The parameters can broadly be classified as related to climate science, damages, discontinuities, and adaptive and preventive costs. In the default version of the model, all of the parameters are modeled as triangular distributions except for the one variable related to the probability of a discontinuity occurring, with is represented by a uniform distribution. More detail on the model equations can be found in Hope (2006, 2011a) and the default minimum, mode, and maximum values for the parameters are provided in Appendix 2 of Hope (2011a). The calibration of these distributions is based on the developer's assessment of the IPCC's Fourth Assessment report and scientific articles referenced in Hope (2011a, 2011b, 2011c). The IWG added an uncertain parameter to the default model, specifically the equilibrium climate sensitivity parameter, which was harmonized across the models as discussed in the 2010 TSD.

In the climate component of the PAGE model, atmospheric CO_2 concentration is assumed to follow an initial rapid decay followed by an exponential decline to an equilibrium level. The parameters treated probabilistically in this decay are the proportion of the anthropogenic CO_2 emissions that enter the atmosphere, the half-life of the CO_2's atmospheric residence, and the fraction of cumulative emissions that ultimately remains in the atmosphere. A carbon cycle feedback is included to represent the impact of increasing temperatures on the role of the terrestrial biosphere and oceans in the carbon cycle. This feedback is modeled with probabilistic parameters representing the percentage increase in the CO_2 concentration anomaly and with an uncertain upper bound on this percentage.

The negative radiative forcing effect from sulfates is modeled with probabilistic parameters for the direct linear effect due to backscattering and the indirect logarithmic effect assumed for cloud interactions. The radiative forcing from CO_2, all other greenhouse gases, and sulfates are combined in a one box model to estimate the global mean temperature. Uncertainty in the global mean temperature response to change in radiative forcing is based on the uncertain equilibrium climate sensitivity parameter and uncertainty in the half-life of the global response to an increase in radiative forcing, which defines the inertia of the climate system in the model. Temperature anomalies in the model vary geographically, with larger increases over land and the poles. Probabilistic parameters are used for the ratios of the temperature anomaly over land relative to the ocean and the ratio of the temperature anomaly over the poles relative to the equator. The PAGE model also includes an explicit sea level component, modelled as a lagged function of the global mean temperature anomaly. The elements of this component that are treated

[19] Based on a coefficients of standardized regression of parameter draws on the SC-CO_2 using FUND 3.8.1 under Ramsey discounting with a pure rate of time preference of one percent and rate of relative risk aversion of 1.5. The 90 percent confidence intervals around the regression coefficients are presented as error bars.

[20] This appendix focuses on the parameters in the PAGE model related to estimating the climate impacts and principle calculation of the monetized damages. There are over 60 additional parameters in the model related to abatement and adaptation, which may be highly relevant for purposes other than estimating the SC-CO_2, but are not discussed here.

probabilistically include: sea level rise from preindustrial levels to levels in the year 2000, the asymptotic sea level rise expected with no temperature change, the predicted sea level rise experience with a temperature change, and the half-life of the sea level rise.

In the economic impacts module, damages are estimated for four categories: sea level rise, economic damages, non-economic damages, and damages from a discontinuity. Each damage category is calculated as a loss proportional to GDP. The model first calculates damages for a "focus region" (set to the European Union) assuming the region's base year GDP per capita. Damages for other regions are assumed to be proportional to the focus region's damage, represented by a regional weighting factor.

Economic damages, non-economic damages, and damages from sea level rise are modeled as polynomial functions of the temperature or sea level impact, which are defined as the regional temperature or sea level rise above a regional tolerable level. These functions are calibrated to damages at some reference level (e.g., damages at 3°C or damages for a ½ meter sea level rise). The specification allows for the possibility of "initial benefits" from small increases in regional temperature. The variables represented by a probability distributions in this specification are: the regional weighting factors; the initial benefits; the calibration point; the damages at the calibration point; and the exponent on the damage functions.

The damages from a discontinuity are treated differently from other damages in PAGE because the event either occurs or it does not in a given model simulation. In the PAGE model, the probability of a discontinuity is treated as a discrete event, where if it occurs, additional damages would be borne and therefore added to the other estimates of climate damages. Uncertain parameters related to this discontinuity include the threshold global mean temperature beyond which a discontinuity becomes possible and the increase in the probability of a discontinuity as the temperature anomaly continues to increase beyond this threshold. If the global mean temperature has exceeded the threshold for any time period in a model run, then the probability of a discontinuity occurring is assigned, otherwise the probability is set to zero. For each time period a uniform random variable is drawn and compared to this probability to determine if a discontinuity event has occurred in that simulation. The additional loss if a discontinuity does occur in a simulation is represented by an uncertain parameter and is multiplied by the uncertain regional weighting factor to obtain the regional effects.

Damages for each category in each region are adjusted to account for the region's forecast GDP in a given model year to reflect differences in vulnerability based on the relative level of economic development. Specifically, the damage estimates are multiplied by a factor equal to the ratio of a region's actual GDP per capita to the base year GDP per capita, where the ratio exponentiated with a value less than or equal to zero. The exponents vary across damage categories and in each case are treated as uncertain parameters.

Finally, in each region damages for each category are calculated sequentially (sea level rise, economic, non-economic, and discontinuity, in that order) and are assessed to ensure that they do not create total damages that exceed 100 percent of GDP for that region. Damages transition from a polynomial function to a logistic path once they exceed a certain proportion of remaining GDP, and the proportion where this transition begins is treated as uncertain. An additional parameter labeled the "statistical value of civilization," also treated as uncertain, caps total damages (including abatement and adaptation costs described below) at some maximum level.

Figure C2 presents results of an analysis from the developers of the PAGE model that examines the uncertain parameters that have the greatest influence on estimates of the SC-CO_2 based on the default version of the model. Although some of the modeling inputs are different for the SC-CO_2 estimates calculated by the IWG, these parameters are likely to remain highly influential in the PAGE modeling results.

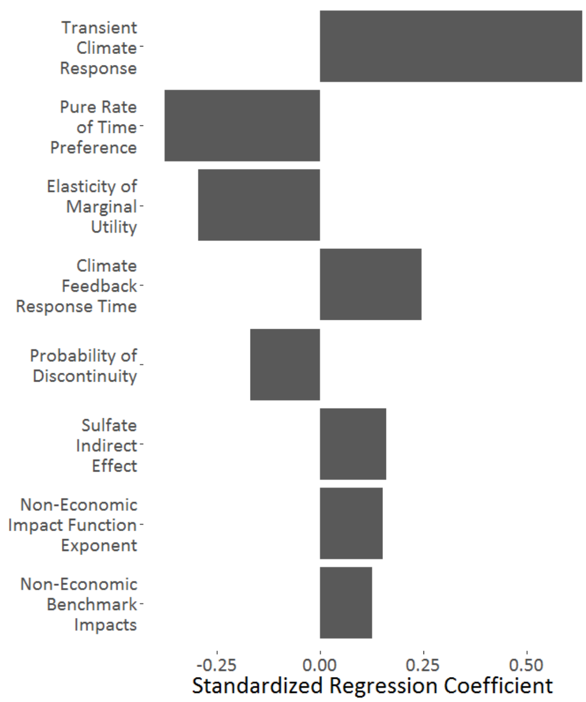

Figure C2: Influence of Key Uncertain Parameters in Default PAGE Model (Hope 2013)[21]

[21] Based on a standardized regression of the parameters. The values give the predicted increase in the SC-CO_2 in 2010 based on a one standard deviation increase in the coefficient, using the default parameters for PAGE09 under Ramsey discounting with an uncertain pure rate of time preference and rate of relative risk aversion.

Response to Comments:
Social Cost of Carbon for Regulatory Impact Analysis
Under Executive Order 12866

Interagency Working Group on Social Cost of Carbon, United States Government

With participation by

Council of Economic Advisers
Council on Environmental Quality
Department of Agriculture
Department of Commerce
Department of Energy
Department of Transportation
Environmental Protection Agency
National Economic Council
Office of Management and Budget
Office of Science and Technology Policy
Department of the Treasury

July 2015

Social Cost of Carbon: Response to Comments

SUMMARY: On November 26, 2013, the Office of Management and Budget (OMB) published a Federal Register notice requesting comments on the Technical Support Document (TSD) entitled *Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866*. The Social Cost of Carbon (SCC) is used to estimate the value to society of marginal reductions in carbon dioxide (CO_2) emissions. This TSD, issued in November, 2013, explained the derivation of the SCC estimates using three integrated assessment models (IAMs) regularly applied in the peer-reviewed scientific literature and provided updated values of the SCC that reflected minor technical corrections to the estimates released in May of that year.

OMB requested that comments be submitted electronically to OMB by January 27, 2014 through *www.regulations.gov*. On that date, OMB issued a subsequent notice extending the comment period until February 26, 2014.

This notice responds to the major comments received and discusses how the Interagency Working Group (IWG) that developed the SCC estimates will approach future updates to the estimates, based on comments received, developments in the academic literature, and advice from external experts.

SUPPLEMENTARY INFORMATION: Rigorous evaluation of benefits and costs is a core tenet of the rulemaking process.[1] It is particularly important in the area of climate change. The current estimate of the SCC has been developed over several years, using the best science available, and with input from the public.

In February 2010, after considering public comments on interim values that agencies used in a number of rules, an interagency working group of technical experts, coordinated by OMB and the Council of Economic Advisers (CEA), released updated SCC estimates. The IWG estimated the updated SCC values using the most widely cited climate economic impact models that are capable of estimating the SCC. Those climate impact models, known as IAMs, were developed by outside experts and published in the peer-reviewed literature. The TSD discusses in detail the models, inputs, and assumptions used in generating the SCC estimates, and the basis for their selection (2010 TSD). Recognizing that the models underlying the SCC estimates would evolve and improve over time as scientific and economic understanding increased, the IWG committed in the 2010 TSD to regular updates of these estimates.

In May of 2013, after all three of the underlying models had been updated and used in the peer-reviewed literature, and agencies had received public comments urging them to update their estimates, the IWG released revised SCC values. The May 2013 estimates are similar to those used by other governments, international institutions, and major corporations. Opportunity for public comment on those estimates

[1] Executive Order 12866 directs that its regulatory principles, which includes assessing the benefits and costs of intended regulations, should be adhered to by Federal agencies "to the extent permitted by law and where applicable." (http://www.archives.gov/federal-register/executive-orders/pdf/12866.pdf)

was previously provided in a number of proposed rulemakings, and any comments received through the rulemaking process were, or will be, addressed by the agencies in the normal course of finalizing those rules.

A slightly revised TSD with minor technical corrections was issued in November, 2013 (2013 TSD). The 2013 TSD was based on the best scientific information on the impacts of climate change available at that time. Consistent with the IWG's commitment to continued refinement of the SCC estimates to ensure agencies appropriately measure the social damages associated with CO_2 emissions as they evaluate the costs and benefits of rules, on November 26, 2013 OMB requested comments on all aspects of the TSD and its use of IAMs to estimate the SCC. OMB noted that it was particularly interested in comments on the following topics:

- the selection of the three IAMs for use in the analysis and the synthesis of the resulting SCC estimates, as outlined in the 2010 TSD;
- the model inputs used to develop the SCC estimates, including economic growth, emissions trajectories, climate sensitivity, and intergenerational discounting;
- how the distribution of SCC estimates should be represented in regulatory impact analyses; and
- the strengths and limitations of the overall approach.

OMB further clarified that it was not requesting comments on the three peer reviewed IAMs themselves; rather OMB was requesting comments on their use in developing the SCC estimates.

1 Introduction

Rigorous evaluation of benefits and costs is a core tenet of the rulemaking process. Since 1981 executive orders have required benefit cost analysis for all significant U.S. Federal regulations, to the extent permitted by law (EOs 12291 and 12866). Estimates of the SCC allow the effects of CO_2 emission changes on society to be counted in benefit cost analysis. Without estimates of the SCC the effect of a change in CO_2 emissions would be considered qualitatively, but could not be quantified in the bottom-line benefit cost estimates. In 2007 the Ninth Circuit Court remanded a fuel economy rule to DOT for failing to monetize the benefits of the CO_2 emissions reductions in its regulatory impact analysis, noting that "the value of carbon emissions reduction is certainly not zero."[2]

In 2009, the Administration launched a process to determine how best to monetize the net effects (comprising both positive and negative effects) of CO_2 emissions and sought to harmonize a range of different SCC estimates across multiple Federal agencies. This process was conducted by an interagency working group made up of Federal agencies likely to issue rules affecting CO_2 emissions and EOP offices that review such rules. The purpose of this process was to ensure that agencies were using the best available information and to promote consistency in the way agencies quantify the benefits of reducing CO_2 emissions, or costs from increasing emissions, in regulatory impact analyses. At the start of the 2009

[2] http://cdn.ca9.uscourts.gov/datastore/opinions/2007/11/14/0671891.pdf

effort, the IWG conducted a preliminary assessment of existing peer-reviewed literature to set interim SCC estimates while it worked on a more comprehensive analysis. When agencies began using these interim values in rulemakings, they solicited comments "on all of the scientific, economic, and ethical issues before establishing improved estimates for use in future rulemakings."[3]

In February 2010, after considering public comments on the interim values and conducting additional technical work, the IWG released improved SCC estimates. These improved SCC estimates were developed using the three most widely cited climate economic impact models. Those climate impact models were developed by outside experts and are the most widely used and widely cited models in the economics literature that link physical impacts to economic damages of CO_2 emissions. The National Academies of Science (NAS) identified these three models as "the most widely used impact assessment models" in a 2010 report (NAS, 2010).

With the release of the 2010 SCC estimates the IWG noted that there remained a number of limitations to the analysis and committed to updating the estimates as the science and economic understanding of climate change and its impacts on society improves over time. In particular, a goal was set to revisit the SCC estimates "within two years or at such time as substantially updated models become available." Subsequent to the release of the 2010 TSD, all three of the models used in the development of the SCC estimates were updated by their (academic) developers, in part, to reflect more recent information on the potential impacts of climate change. The three models remain the most widely cited models capable of estimating the SCC.

Since the publication of the interim estimates in 2009, the IWG's SCC estimates have been used in 34 proposed rulemakings that provided opportunity for public comment. Federal agencies and OMB have continued to review public comments on the SCC estimates that are received through the notice and comment rulemaking process. Public comments received on proposed rulemakings using the 2010 SCC estimates, among other comments, urged the IWG to update the SCC estimates to reflect the newest versions of the models being used in the peer-reviewed scientific literature.[4] In response to these comments and consistent with the 2010 commitment to periodically revise the SCC estimates, in 2013 the IWG released an update to the SCC estimates that maintained the same methodology underpinning the previous estimates, but applied the most current versions of the three IAMs.

That same year, in response to public and stakeholder interest in the SCC estimates, OMB announced it would provide an additional opportunity, in addition to those available in proposed rulemakings, for public comment on the SCC estimates. Over the 90-day comment period[5], OMB received 140 unique sets of comments and over 39,000 form letter submissions through two letter writing campaigns. The comments covered a wide range of topics including the technical details of the modeling, the aggregation and

[3] For example, the proposed rulemaking for Model Year 2012-2016 Light-Duty Vehicle Greenhouse Gas Emissions Standards. http://www.gpo.gov/fdsys/pkg/FR-2009-09-28/pdf/E9-22516.pdf.
[4] See Docket ID: EPA-HQ-OAR-2010-0660-10002 (p 4); EPA-HQ-OAR-2010-0660-10888 (p 26); EPA-HQ-OAR-2010-0799-9519 (p 10). Documents are available in www.regulations.gov.
[5] OMB originally provided a 60-day comment period but that was subsequently extended, in response to stakeholder requests, for an additional 30 days.

presentation of the results, and the process by which the SCC estimates were derived. The form letters contained a short paragraph supporting the 2013 update. The unique comment letters offered a wide range of perspectives on the process, methodology, and results, including both support and opposition. Commenters also provided constructive recommendations for potential opportunities to improve the SCC estimates in future updates. In this context, the IWG is reconfirming its commitment to periodic review and update of the methodology and estimates to ensure that they continue to reflect the best available science and economics.

The science underlying the assessment and valuation of climate change impacts is constantly evolving. Since the publication of the initial SCC estimates in 2010, the representation of the science and economic consequences of climate change in the three IAMs has improved. The 2013 SCC technical update allowed the SCC estimates to reflect these improvements. However, as explained in the 2013 TSD, this update was limited in scope to those improvements available in more recent versions of the IAMs. As such, there remain additional opportunities for technical improvements to the SCC estimates that should be considered for future updates.

As noted above, commenters provided a wide range of perspectives and technical input on how to further refine the SCC estimates. To help synthesize the technical information and input reflected in the comments, and to add additional rigor to the next update of the SCC, the IWG plans to seek independent expert advice on technical opportunities to improve the SCC estimates, including many of the approaches suggested by commenters and summarized in this document. Specifically, the IWG plans to ask the National Academies of Sciences, Engineering, and Medicine to examine the technical merits and challenges of potential approaches to improving the SCC estimates in future updates. Input from the Academies, informed by public comments and the peer-reviewed literature, will help to ensure that the SCC estimates used by the federal government continue to reflect the best available science and methodologies.

The Academies' review will take some time, during which Federal agencies will have a continued need for estimates of the SCC to use in benefit-cost analysis. After careful evaluation of the full range of comments and associated technical issues detailed below, the IWG continues to recommend the use of the current SCC estimates[6] in regulatory impact analysis until revisions based on the many thoughtful public comments we have received and the independent advice of the Academies can be incorporated into the estimates. We believe the current estimates continue to represent the best scientific information on the impacts of climate change available in a form appropriate for incorporating the damages from incremental CO_2 emissions changes into regulatory analyses.

[6] Concurrently with this document, the IWG is releasing a minor technical revision to the estimates, which is explained in a technical addendum below. The current SCC estimates are contained in the *Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866 (Revised July 2015)* which is available at *http://whitehouse.gov/sites/default/files/omb/inforeg/scc-tsd-final-july-2015.pdf.*

The remainder of this Response to Comments document provides topic specific summaries of the comments received followed by a response. The comments have been categorized into the following topics, which are addressed in turn:

- Choice of Integrated Assessment Models and Damage Functions
- Climate Science
- Socio Economic and Emissions Scenarios
- Discount Rates
- Aggregation of Results and Selection of Final Estimates
- Consideration of Uncertainty
- Use of Global vs. Domestic SCC Estimates
- Other Technical Areas of Comment
- Process by which the SCC Estimates were Developed

These nine major topic sections are further divided into brief summaries of specific comment areas, each followed by a response. Subsequently, there is a brief technical addendum explaining two minor revisions to the TSD.

2 Choice of Integrated Assessment Models and Damage Functions

Many commenters addressed the IAMs used to estimate the SCC. Several commenters recommended improvements to the existing IAMs and their damage functions, which monetize the damages associated with the physical impacts of climate change. Finally, a few commenters discussed the value to society of the goods and services whose production is associated with CO_2 emissions.

(1) The IWG's choice of IAMs used to estimate the SCC

A number of commenters were generally supportive of the choice of the three IAMs used in developing the SCC. For example, a letter signed by several commenters noted that these IAMs are "reasonably based on current scientific and economic knowledge" and are "widely cited and accepted in the academic community." One commenter said the models reflect "the best available, peer-reviewed science to tally the benefits and costs of specific regulations with impacts on CO_2 emissions. The IAMs include benefits and costs that have been quantified to date."

Other commenters voiced concern that the economic damages estimated by the IAMs are too uncertain to be useful for policy analysis. Several of these commenters included quotations from Pindyck (2013) and argue that the current IAMs and their damage functions lack sufficient theoretical or empirical foundations. For example, one commenter stated that "… The loss functions in PAGE and FUND, the other two models used by the Interagency Working Group, are more complex but equally arbitrary ... there is no pretense that the equations are based on any theory." Another commenter wrote, "The outputs of the three integrated assessment models (IAMs) are dependent on arbitrary and subjective assumptions used for data inputs."

Some commenters suggested that one or more of the models should be rejected. For example, some cited Dayaratna and Kreutzer (2013) in arguing that the DICE model is "flawed beyond use for policymaking." Others argued that both PAGE and DICE should be omitted because both include "little-to-no CO_2 fertilization benefit" in estimating agricultural damages. Another commenter suggested all three models be rejected because "… DICE and PAGE are too aggregated to represent research on climate impacts in any detail; they offer only their developers' guesses about how to reduce the vast, multi-dimensional array of climate damages to a few summary, monetized impacts", and "FUND … attempts a higher level of disaggregation, but produces damage results that are too low to be consistent with current climate science."

Finally, a few commenters suggested that other IAMs should be considered for any future SCC updates. Sometimes this was a generic suggestion such as "updates to the SCC should also consider other models that are similarly peer reviewed and based on the state of the art of climate-economic modeling." A model that was mentioned by a few commenters was the World Bank's Environmental Impact and Sustainability Applied General Equilibrium (ENVISAGE) Model. One commenter suggested the use of the model, Climate and Regional Economics of Development (CRED).

A few commenters criticized the TSD for failing to adequately explain or justify the choice of models and/or inputs used to run the models. For example, one commenter wrote, "… adequate justification is not currently provided for some aspects of the modeling. … For example, justification is lacking for ... use of an average 550 ppm scenario, constant discount rates, EMF-22 versus other published scenarios, FUND and PAGE probabilistic modeling, and a variety of 2013 revisions to the individual models …" Another commenter cited a 1981 D.C. Circuit U.S. Court of Appeals decision that an agency "must provide a complete analytic defense of its model [and] respond to each objection with a reasoned presentation" and must demonstrate "rational connections between factual inputs, modeling assumptions, modeling results and conclusions drawn from those results." A third commenter cited the Administrative Procedure Act (APA), arguing that the "use of the SCC estimates in rulemaking will not meet the requirements of the APA as interpreted by the courts because the IWG and OMB have not provided a rational connection or sufficient justification for the models, data inputs and assumptions used to create the SCC estimates."

Response

The IWG agrees with those commenters who believe the choice of the three IAMs—DICE, FUND, and PAGE—was the most appropriate for the purpose of estimating the SCC. The IWG made this determination when it began developing the SCC estimates in 2009-2010. DICE, FUND, and PAGE are the most widely used and widely cited models in the economic literature that link physical impacts to economic damages for the purposes of estimating the SCC. As stated in the 2010 TSD:

> These models are frequently cited in the peer-reviewed literature and used in the IPCC assessment. … These models are useful because they combine climate processes, economic growth, and feedbacks between the climate and the global economy into a single modeling framework. … Other IAMs may better reflect the complexity of the science in their modeling frameworks but do not link physical impacts to economic damages.

In addition, the National Academies of Science (NAS) identified these three models as "the most widely used impact assessment models" in a 2010 report (NAS, 2010). Furthermore, in a comprehensive literature review and meta-analysis conducted in 2008, the vast majority of the independent impact estimates that appeared in the peer-reviewed literature were derived from FUND, DICE, or PAGE (Tol, 2008).

While the development of the DICE, FUND and PAGE models necessarily involved assumptions and judgments on the part of the modelers, the damage functions are not simply arbitrary representations of the modelers' opinions about climate damages. Rather they are based on a review by the modelers of the currently available literature on the effects of climate change on society. The conclusions that the modelers draw from the literature, and the bases for these conclusions are documented, and all three models are continually updated as new information becomes available. While we recognize that there are limitations with these models, including some of those discussed in Pindyck (2013), nonetheless IAMs provide valuable information for regulatory impact analysis. In a recent article in the peer-reviewed literature, Weyant (2014) addressed this issue as follows:

> While Pindyck's observations about the empirical weaknesses of IAMs or calculations of the SCC are worthy of careful study, the conclusion that IAMs are therefore useless fundamentally misconceives the enterprise. IAMs and the SCC are conceptual frameworks for dealing with highly complex, non-linear, dynamic, and uncertain systems. The human mind is incapable of solving all the equations simultaneously, and modeling allows making "If…, then…" analyses of the impacts of different factors. The models have provided important insights into many aspects of climate-change policy.

The IWG thus believes that it was appropriate to base the SCC estimates on the DICE, FUND and PAGE models. Moving forward, the IWG will continue to follow and evaluate the latest peer reviewed literature applying IAMs. The IWG will seek external expert advice on the technical merits and challenges of using additional models (e.g., CRED, ENVISAGE) to estimate the SCC and/or removing existing models from the ensemble (DICE, FUND, and PAGE) used to estimate the SCC.

Finally, the IWG disagrees with the comment that insufficient justification has been provided for the models, data inputs, and assumptions used to estimate the SCC. The IWG has regularly and repeatedly provided detailed explanations and justifications for the data, assumptions, and models used to estimate the SCC. The 2010 TSD thoroughly detailed each of these aspects, justified their use, and elucidated their limitations. The 2013 TSD provided a detailed explanation of updates and revisions made to the SCC. The additional OMB public comment solicitation provided a further opportunity for the public to comment on the data, assumptions, and models used in developing the SCC estimates; in this Response to Comment the IWG is responding to those comments received. Thus, the IWG has provided clear, transparent analytic defenses of its estimates, explained the rational connections that underlie these estimates, and responded to public comments.

The 2010 TSD provides a complete explanation of the entire modeling exercise, including a description of the chosen integrated assessment models (IAMs) and why they were selected, how the harmonized modeling decisions were developed, how the sources of the data inputs were selected, and how the model results were aggregated to the final four point estimates that are used in regulatory analysis. For example, Section III A. of the TSD describes, in detail, the structure and connections within the IAMs (DICE, FUND, and PAGE), and the features that make them relevant and appropriate for estimating the SCC. As described in the 2010 TSD, after critical evaluation the IWG concluded that it is reasonable to use these three models from the peer-reviewed literature for the purpose of estimating the SCC. Section III of the 2010 TSD also describes, in detail, other relevant modeling inputs adopted by the IWG, the basis for the specific inputs used, and how these inputs are connected to the modeling and estimates of the SCC. For example, see Section III D. of the 2010 TSD for discussion about the IWG's analysis, development, and application of the distribution for the equilibrium climate sensitivity parameter; Section III E. for discussion about the IWG's analysis, selection, and, application of socioeconomic and emissions scenarios; and Section III F. for discussion about the IWG's literature search, analysis, and selection of discount rates. In addition, in Section V of the 2010 TSD the IWG described potential limitations of the analysis and made clear the resulting implications for the SCC estimates, based on the IWG's critical examination of the models and their underlying assumptions.

(2) Recommendations for improving the current IAMs or damage functions

Many commenters suggested improvements to one or more of the models before future SCC updates. Many of these commenters believe that the current SCC estimates underestimate the damages induced by climate change because of incomplete or missing treatment of a number of damage categories. Suggestions for additional damage categories include: ocean acidification, spillover effects from displaced persons, increased variability in weather patterns, wildfires, "catastrophic" damages stemming from exceedance of various "tipping points," loss of species and habitat diversity, cultural impacts, health effects from increased air pollution, and impacts on global security, among others. Commenters also questioned whether the models adequately addressed linkages between the damage categories. One Commenter suggested the use of the aggregate damage function introduced by Weitzman (2010) as an alternative specification relating mean temperature change and GDP loss.

Commenters disagreed about whether the IAMs overestimate or underestimate CO_2 fertilization effects in the agriculture and forestry sectors. For example, one commenter wrote "only one of the three IAMs used by the IWG has any substantial impact from CO_2 fertilization, and the one that does, underestimates the effect by approximately 2-3 times," referencing Idso (2013). However another commenter argued that "the models do not reflect recent research on agricultural changes, which suggests that CO_2 fertilization is overestimated, particularly in the FUND model, and that much, if not all, of the fertilization benefits may be cancelled out by negative impacts on agriculture."

Response

To date, the IWG has accepted the models as currently constituted, and omitted any damages or beneficial effects that the model developers themselves do not include. The IWG recognizes that none of the three IAMs fully incorporates all climate change impacts, either positive or negative. Some of the effects referenced by commenters (e.g., "catastrophic" effects, disease, and CO_2 fertilization) are explicitly modeled in the damage functions of one or more of the current models (although the treatment may not be complete), and the model developers continue to update their models as new research becomes available. In fact, the IWG undertook the 2013 revision because of updates to the models, which include new or enhanced representation of certain impacts, such as sea level rise damages. In addition, some of the categories mentioned by commenters are currently speculative or cannot be incorporated into the damage function for lack of appropriate data. Using an ensemble of three different models was intended to, at least partially, address the fact that no single model includes all of the impacts. We recognize that there may be effects that none of the three selected models addresses (e.g., impacts from ocean acidification) or that are likely not fully captured (e.g. catastrophic effects).

The IWG also recognizes that the impacts of climate change on agriculture is an area of active research and that methodological and data challenges persist. As a result there is uncertainty as to the magnitude of these impacts and the role of interactions between changes in the climate and other factors, such as CO_2 fertilization, temperature, precipitation, ozone, pests, etc. Additionally, these effects are likely to vary widely across regions and crops. However, with high confidence the IPCC (2013) stated in its Fifth Assessment Report (AR5) that "[b]ased on many studies covering a wide range of regions and crops, negative impacts of climate change on crop yields have been more common than positive impacts." As noted above, the IWG's approach to date has been to rely on the damage functions included in the three IAMs by their developers.

The IWG agrees that it is important to update the SCC periodically to incorporate improvements in the understanding of greenhouse gas emissions impacts and will continue to follow and evaluate the latest science on impact categories that are omitted or not fully addressed in the IAMs. Also, the IWG will seek external expert advice on the technical merits and challenges of potential approaches to update the damage functions in future revisions to the SCC estimates.

(3) Value of goods and services whose production is associated with CO_2 emissions

Some commenters felt that the SCC estimates should include the value to society of the goods and services whose production is associated with CO_2 emissions. Many of these commenters mentioned goods produced using fossil fuels, such as "plastics, chemicals, nitrogen fertilizer, steel, aluminum, synthetic rubber for tires, glass, pharmaceuticals, and paper." One commenter argued for including the benefits to "regions that depend on employment from energy intensive industry, regions dependent on fossil fuels for heating, cooling, food production and other components associated with preserving their standard of living and regions that are in need of low cost fossil fuels to enable the economic development improving their standard of living." Similarly, other commenters focused on the negative consequences of regulating CO_2 emissions, such as the potential effect on energy prices, economic growth, or international competitiveness. One commenter suggested the inclusion of "… the social costs and economic dislocations that could result from carbon reduction policies that would eliminate fuel options such as coal, the social costs associated with higher electricity prices, and the economic and security risks associated with electric reliability problems."

Response

Rigorous evaluation of benefits and costs is a core tenet of the rulemaking process. The IWG agrees that these are important issues that may be relevant to assessing the impacts of policies that reduce CO_2 emissions. However, these issues are not relevant to the SCC itself. The SCC is an estimate of the net economic damages resulting from CO_2 emissions, and therefore is used to estimate the benefit of reducing those emissions.

A rule that affects CO_2 emissions may also affect the production or consumption of goods and services, in which case it could create costs and benefits for businesses and households that either produce or use those goods and services. These costs and benefits are important to include in an analysis of the rule's impacts, but are not a result of changes in CO_2 emissions. The SCC is not a measure of social welfare from the consumption of goods and services whose production results in CO_2 emissions, or other positive or negative externalities associated with the production of those goods and services.[7] In other words, the SCC is just one component of a larger analysis that includes consideration of many other potential impacts, including labor market changes, energy security, electricity reliability, and changes in emissions of other pollutants, among others.

3 Climate Science

Comments on the climate science components of the modeling fall into three broad areas: the specification of the equilibrium climate sensitivity parameter, the formulation and parameterization of other physical science components in the IAMs, and uncertainty in climate science and climate modeling. In addition, a number of the commenters generally encouraged continued updating of the SCC to maintain the best scientific understanding of the relevant earth system processes as new findings emerge.

(1) Climate Sensitivity

The equilibrium climate sensitivity (ECS) parameter is a measure of the climate's responsiveness to increased concentrations of greenhouse gases in the atmosphere. Specifically, the ECS is the long-term increase in the annual global-average surface temperature from a sustained doubling of the atmospheric CO_2 concentration relative to pre-industrial levels. Several commenters supported the IWG approach of calibrating the distribution of Roe and Baker (2007) to the IPCC (2007) Fourth Assessment Report (AR4) consensus statement on the ECS. However, many commenters, including many of those that approve of the IWG's basic approach, suggest updating this modeling input. The majority of these commenters suggest incorporating new research published since the 2010 TSD was released. Some commenters noted that in its Fifth Assessment Report the IPCC has revised its discussion of the likely range of climate sensitivity compared to AR4 (IPC 2013). Other commenters pointed to individual papers, such as Otto et al. (2013), which present lower and more constrained probability density functions (pdfs) than either the AR4 or AR5 consensus statements, in support of the commenters' suggestion that the pdf used by the IWG was biased high. Some commenters suggested that certain recent papers (e.g., Loehle, 2014; Otto et

[7] Similarly, the SCC does not capture benefits to society from goods and services that reduce CO_2 emissions, or other co-benefits from reducing emissions such as reduced particulate matter pollution. Those benefits are treated elsewhere in a benefit cost analysis.

al., 2013; Aldrin et al., 2012) may be especially informative because they rely on recent historical temperature measurements. A couple of commenters suggested that the mean of the climate sensitivity pdf used by the IWG was too low, because the climate models do not take into account poorly understood climate system feedbacks and tipping points.

Response

The IWG is aware that this is an active area of research and remains committed to updating the SCC estimates to incorporate new scientific information and accurately reflect the current state of scientific uncertainty regarding the ECS. While we agree with commenters that the ECS distribution, along with other climate modeling inputs to the SCC calculation, should be updated periodically to reflect the latest scientific consensus, care must be exercised in selecting an appropriate range of estimates for this important parameter. Many studies estimating climate sensitivity have been published, based on a variety of approaches (instrumental record, paleoclimate observations, models, etc.). These individual studies report differing values and provide different information. Picking a single study from the high or low end of the range, or even in the middle, will exclude relevant information. A valid representation of uncertainty regarding climate sensitivity should be obtained from a synthesis exercise such as that done by the IPCC that considers the full range of relevant studies.

At the time the 2013 SCC update was released, the most authoritative statement about ECS appeared in the IPCC's AR4. Since that time, as several commenters noted, the IPCC issued a Fifth Assessment Report that updated its discussion of the likely range of climate sensitivity compared to AR4. The new assessment reduced the low end of the assessed likely range (high confidence) from 2°C to 1.5°C, but retained the high end of the range at 4.5°C. Unlike in AR4, the new assessment refrained from indicating a central estimate of ECS. This assessment is based on a comprehensive review of the scientific literature and reflects improved understanding, the extended temperature record for the atmosphere and oceans, and new estimates of radiative forcing.

Several of the post-AR4 studies highlighted by some commenters were cited in the AR5 assessment. In particular, both Aldrin et al. (2012) and Otto et al. (2013) were cited in both Chapter 10 and Chapter 12 of the AR5 Working Group I assessment. Eight of the authors of Otto et al. (2013), including the lead author, were authors of Chapter 12 for AR5's Working Group I and one was a lead author for the chapter. Hence it is clear that the IPCC considered Otto et al. (2013) in its synthesis of literature on the ECS. More broadly, the AR5 climate sensitivity distribution likely incorporates much of the literature identified by the commenters. The IWG will continue to follow and evaluate the latest science on the equilibrium climate sensitivity and seek external expert advice on the technical merits and challenges of potential approaches prior to updating the ECS distribution in future revisions to the SCC estimates, including (but not limited to) using the AR5 climate sensitivity distribution for the next update of the SCC.

(2) Other Physical Science Components of the Integrated Assessment Models

We define the physical science components of the models to include the modeling of physical impacts, such as changes in mean global temperature or sea level rise. This definition excludes the functions in the models that translate those physical endpoints into economic damages, which is addressed above in the discussion of damage functions. Some commenters expressed approval of the physical science components of the models but others criticized specific components as being overly simplified or incomplete. For example, some commenters suggested that IAMs under-represent the potential for future damages by concentrating on changes in annual and global mean climate indicators, when changes in variability, or interactions between changes in the mean and natural variability, could be key components in determining future damages. Others noted the need for more explicit representation of the potential for low-probability, high impact "catastrophes," with one commenter calling for better modeling of multiple "tipping points" at the climatic thresholds indicated by the most recent scientific literature. Another commenter suggested that the IAMs assign too high a probability to "catastrophic" and extreme events, such as "ocean circulation shutdown, catastrophic sea level rise, and runaway climate change."

The comments regarding the representation of the carbon cycle were mixed. One commenter suggested that the highly simplified carbon cycles in the IAMs may lead to an underestimation of atmospheric CO_2 concentrations over time because they do not adequately capture the feedback of climate change on the strength of carbon sinks, citing Kopp and Mignone (2012). Other commenters suggested that the ocean uptake of CO_2 has actually been greater than predicted and thus the models may be overestimating atmospheric CO_2 concentrations.

A few commenters suggested that changes in the temperature response functions across model versions are unsupported by evidence or research.[8] For example, two commenters suggested that a change in the triangular probability distribution of the transient climate response function in PAGE was largely subjective and lacked adequate supporting citations. Another noted that, in the FUND model, the increased rate of temperature change for any given climate sensitivity was inconsistent with recent observations, which the commenter suggests show the rate of warming to be slower than predicted. One commenter suggested that the version of the DICE model used may overestimate sea level rise relative to AR5 projections or estimates projected by the MAGICC climate model because of DICE's reliance on an outdated semi-empirical methodology that uses models of reduced complexity in conjunction with statistical relationships between sea level and climate forcing.[9] Finally, one commenter suggested that the entire physical climate and greenhouse gas concentration functions in the IAMs should be replaced by functions from other models. The commenter mentions the more detailed representations such as MAGICC, SNEASY, or BEAM, which would have simultaneous implications for the carbon cycle, sea level rise, and/or temperature response rates.[10]

Response

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[8] While the ECS determines the long-term magnitude of the climate's response to changes in atmospheric concentrations of GHGs, the IAM's temperature response functions model the near-term dynamics of how the climate responds to increasing atmospheric concentrations.

[9] MAGICC is the Model for the Assessment of Greenhouse Gas Induced Climate Change. For more information see Meinshausen et al. (2011).

[10] For more information on the SNEASY model see Urban and Keller (2010). For more information on the BEAM model see Glotter et al. (2014).

A key objective of the IWG was to draw from the insights of the three models while respecting the different approaches to linking GHG emissions and monetized damages taken by modelers in the published literature. After conducting an extensive literature review, the interagency group selected three sets of input parameters (climate sensitivity, socioeconomic and emissions trajectories, and discount rates) to use consistently in each model. All other model features were left unchanged, relying on the model developers' best estimates and judgments, as informed by the then-current literature. While the IAMs are periodically updated, the rapid pace of research in the area of climate science means that at any given time there may be new research that has not yet been incorporated into one or more models. Thus, while a given model may not always reflect the most recent research regarding any given climate subsystem, the IWG concluded that, at the time, the IAMs collectively represented the state of the science by bringing all these systems together into a single framework.

A benefit of using an ensemble of three models is that they cover a range of potential outcomes as expressed in the literature. For example the three models used collectively span a range of carbon cycle and climate change responsiveness that reflects the uncertainty in the literature.

With regards to comments on the temperature response function, the past 15 years of observed atmospheric temperatures cannot be compared directly to climate model simulations because (1) observed temperatures were influenced by volcanic eruptions that were not included in simulations because the timing and spatial distribution of eruptions are not known in advance; and (2) the last 15 years of atmospheric temperatures have been strongly influenced by natural climate variability due to oceanic fluctuations, such as the El Niño Southern-Oscillation; models include this variability, but no attempt is made to synchronize the models' timing of this variability with observed variability. In other words, while the models incorporate variability around a trend over time, they cannot predict how that variability affects measured temperatures in a specific year.

Regarding the criticisms by commenters of the sea level rise projections in DICE, the IWG recognizes that sea level rise projections are also an area of ongoing research. One key issue involves projections of melt from the Greenland and West Antarctic ice sheets. The IPCC AR5 report notes there is a possibility of sea level rise "substantially above" their best estimate of a likely range because of uncertainties regarding the response of the Antarctic ice sheet (AR5 Working Group I, Chapter 13). In AR5 the IPCC also discusses semi-empirical methods, stating a low confidence in projections based on such methods, which calibrate a mathematical model against observations rather than projecting individual processes. However, the IPCC did not entirely discount these methods. Further supporting the use of semi-empirical methods, the U.S. National Climate Assessment uses an average of the high end of semi-empirical projections in order to define their "Intermediate-High" Scenario (Parris et al., 2012). Therefore, it is reasonable for one out of three models used by the IWG to include some reliance upon semi-empirical methods.

The IWG is aware that more sophisticated yet still relatively simplified climate models, such as MAGICC, could be used to replace the highly simplified climate science components of the three IAMs. However, given the range of climate models available and the technical issues associated with such a change, replacing the climate modules or other structural features of the IAMs requires additional investigation before it can be applied to SCC estimation. The IWG will continue to follow and evaluate the latest science on climate modeling and seek external expert advice on the technical merits and challenges of potential approaches to updating this component of the IAMs in future revisions to the SCC estimates.

We agree with the commenters who suggested the IAMs do not fully capture the impacts associated with changes in climate variability and weather extremes. For example, as discussed in the 2010 TSD, the calibrations in FUND and DICE do not account for increases in climate variability that may occur and would affect the agricultural sector. Similarly, we agree that the models' functional forms may not adequately capture potentially discontinuous "tipping point" behavior in Earth systems. In fact, large-scale earth system feedback effects (e.g., Arctic sea ice loss, melting permafrost, large scale forest dieback, changing ocean circulation patterns) are not modeled at all in one IAM, and are imperfectly captured in the others. This limitation of the three IAMs is discussed extensively in the 2010 TSD, and again in the 2013 update. The SCC estimate associated with the 95^{th} percentile of the distribution based on the 3 percent discount rate is included in the recommended range partly to address this concern. The IWG will continue to follow and evaluate the latest science on climate variability and potential tipping points, and seek external expert advice on the technical merits and challenges of potential approaches to improve the representation of these components of the modeling in future revisions.

(3) Uncertainty in Climate Science

A number of commenters discussed limitations in the current state of climate science and climate modeling generally. Some expressed skepticism about the link between anthropogenic CO_2 emissions and climate change. Others suggested that the SCC estimates are unreliable because climate modeling in general is unreliable and too uncertain for use in regulatory analysis. These commenters suggested that the climate models are flawed, have not been properly validated, can disagree with each other, and have biased projections. In many cases these commenters suggested that a recently observed reduction in the rate of surface temperature warming is evidence that the current generation of climate models should not be used to estimate the SCC. One commenter suggested that the SCC estimates don't adequately take into account the potential of a significantly cooler future climate absent GHG emissions, while another suggested that mainstream climate scientists have not appropriately considered the prediction of a grand solar minimum that could lead to a cooling cycle.

Some commenters voiced general criticisms of the IWG approach to the ECS due to the uncertainty about the shape of the climate sensitivity distribution and the sensitivity of the SCC estimates to the specification of the ECS distribution. One commenter suggested that the IPCC has not made progress in reducing uncertainty about climate sensitivity and therefore the IPCC consensus should not be used. Several commenters objected to the IWG use of the Roe and Baker (2007) distribution for the ECS. One of these commenters cited Pindyck (2013), stating that feedback loops within the climate system are largely unknown and therefore the shape of the distribution is unknown. The commenter suggested that Roe and Baker's assumption of a normally distributed climate feedback factor may not be theoretically correct, and suggested the use of alternative distributions. The commenter was particularly concerned that the use of a right-skewed distribution for the ECS would lead to an overestimate of the mean SCC if the ECS distribution would be more appropriately modeled as symmetric, though another commenter suggested that the Roe and Baker approach correctly captured the right-skewed nature of the distribution.

Response

Links between CO_2 and temperature are established beyond question by laboratory measurements, physical theory, paleoclimate observations, instrumental observations, and observations of other planets. Climate change and its impacts, such as sea level rise, have been exhaustively documented, and synthesized internationally by the IPCC and domestically by the U.S. National Climate Assessment. Based on the wide acceptance of these conclusions in the scientific community, the IWG believes that: (1) anthropogenic emissions of greenhouse gases are causing atmospheric levels of greenhouse gases in our atmosphere to rise to levels unprecedented in human history; (2) the accumulation of greenhouse gases in our atmosphere is exerting a warming effect on the global climate; (3) there are multiple lines of evidence, including increasing average global surface temperatures, rising ocean temperatures and sea levels, and shrinking ice in glaciers, ice sheets, and the Arctic, all showing that climate change is occurring, and that the rate of climate change in the past few decades has been unusual in the context of the past 1000 years; (4) there is compelling evidence that anthropogenic emissions of greenhouse gases are the primary driver of recent observed increases in average global temperature; (5) atmospheric levels of most greenhouse gases are expected to continue to rise for the foreseeable future; and (6) risks and impacts to public health and welfare are expected to grow as climate change continues, and that climate change over this century is expected to be greater compared to observed climate change over the past century.

While there are inherent uncertainties associated with modeling climate systems over long time spans, the general circulation models (GCMs) upon which estimates of ECS and other climate science research are based have been extensively evaluated. For example, since 1989 the DOE has had a large program (The Program for Climate Model Diagnosis and Intercomparison) dedicated to evaluating these models.

Predictions of future solar activity are highly uncertain. However, even if a new solar minimum of the magnitude of the Maunder minimum (the solar low during the Little Ice Age) were to occur, its cooling tendency would be much less than the warming tendency from human greenhouse gases (e.g., Feulner and Rahmstorf, 2010).

The ECS parameter is a useful parameter for summarizing the strength of the climate system's response to accumulating GHG concentrations in the atmosphere. However, it is influenced by many highly complex and uncertain natural processes, some of which adjust over very long periods of time. Therefore, persistent uncertainty about the ECS is not surprising. Furthermore, persistent uncertainty does not suggest an absence of useful information. However, the IWG does not agree that progress has not been made in reducing this uncertainty. Over the last 30 years the scientific community has elucidated many aspects of the climate system's response to GHGs accumulating in the atmosphere. While the AR5 "likely" range is slightly larger than that of AR4, the assessment presented greater confidence in the tails. AR5 found that climate sensitivity is very unlikely to be greater than 6°C, whereas AR4 stated that the "lack of strong constraints limiting high climate sensitivities prevents the specification of a 95th percentile bound." Similarly, while the AR5 and the IPCC's (2001) Third Assessment Report (TAR) bounds look similar, the TAR bounds were presented as a range without estimated probabilities.

In response to the commenter citing Pindyck on climate feedbacks and the shape of the ECS distribution, we agree that potential climate feedbacks and their strength are uncertain. However, the IWG chose a distribution from the peer-reviewed literature based on its evaluation of the scientific literature and the relationship between this distribution and IPCC range of the ECS. Regarding the skewness of the calibrated ECS distribution, this characteristic is common among the many approaches that have been used to study the ECS distribution and is not unique to the theoretical approach used by Roe and Baker to define the functional form of their distribution. Consistent with the AR4 discussion on limiting the distribution to a range considered possible by experts, such as from 0°C to 10°C, the IWG truncated the distribution at 10°C (Hegerl 2007, p 719).

4 Socioeconomic and Emissions Scenarios

Several commenters discussed the socioeconomic-emissions scenarios that are used as inputs for the IAMs. One commenter voiced general support for the IWG's approach, noting that the "use of EMF-22 [scenarios] represents a carefully considered and scientifically defensible decision." Other comments can be grouped into three main categories: the socioeconomic-emissions scenarios should be updated; concerns with the selected scenarios, including potential inconsistencies with other aspects of the modeling; and future updates of the scenarios should include a formal uncertainty analysis.

(1) The socioeconomic-emissions scenarios should be updated

A number of commenters recommended that the scenarios be updated to reflect newer modeling results. Some comments suggested that the SCC should be estimated using the scenarios in the IPCC's Fifth Assessment Report. In some cases the comments specifically suggested use of the representative concentration pathways (RCPs) and the associated shared socioeconomic pathways (SSPs) that were developed to identify a range of future socioeconomic scenarios that could lead to the RCPs. In other cases the commenters did not specify which AR5 scenarios should be used. In addition to the development of the RCP/SSP scenarios, the IPCC supported the AR5 assessment through an open call for qualified scenarios produced since the publication of AR4. The result of the open call was a database of more than 1,200 scenarios from 32 models that represent both "business-as-usual" (BAU) and policy cases, which were used extensively by Working Group III.

Response

OMB guidance in Circular A-4 requires benefits and costs to be computed relative to a baseline that represents "the best assessment of the way the world would look absent the proposed action." The IWG determined that BAU socioeconomic scenarios best reflect this approach. While the IWG agrees that, all else equal, the baseline used for the SCC calculation should be updated periodically to reflect the latest projections of BAU scenarios, the RCP/SSP scenarios used in support of AR5 may not be easily adaptable for use in SCC modeling.

To understand why, it is important to note some key differences between the criteria used by the IWG to select socioeconomic-emissions scenarios and what the RCP/SSP scenarios represent and how they were developed. Each scenario in the EMF-22 exercise used by the IWG was clearly identified as reflecting a reference case BAU or a specific CO_2 stabilization scenario. Lacking data on the probabilities of specific scenarios, the IWG chose four BAU scenarios and one scenario representing stabilization at 550 ppm CO_2-e and weighted them equally in its analysis. The IWG acknowledges that this is not a precise characterization of the baseline but believes it is a reasonable approach at present, in light of data limitations.

Some of the AR5 scenarios differ from these scenarios in ways that make them difficult to adapt to the SCC context. An ad-hoc group was formed in anticipation of AR5 to develop new scenarios to support climate impacts, adaptation, and vulnerability research. The initial work focused on the development of RCPs, which represent a wide range of potential radiative forcing pathways over the 21st century. The SSPs are a series of human development pathways that could lead to radiative forcing pathways described by the RCPs. The RCPs are not based on a fixed future path of key socioeconomic parameters, which means that multiple SSPs are associated with an RCP. No assessment was made as to the likelihood of any particular RCP being realized, but some of the scenarios clearly would require large-scale global mitigation efforts to be achieved and U.S. involvement in these efforts may be necessary for their success.

In other words, the developers did not assign likelihoods that the various scenarios would achieve the RCPs in the absence of policy interventions, which means that it is not clear which scenarios could reasonably serve as BAU projections. Therefore, using the RCP/SSP scenarios would require the IWG to conduct an assessment of which RCP/SSPs represent BAU scenarios, or of the probability that each scenario occurs in a BAU case. The IWG believes that data are currently lacking to conduct such an assessment.

The IWG will continue to follow and evaluate the latest science on socioeconomic-emissions scenarios and seek external expert advice on the technical merits and challenges of potential approaches to update these scenarios in future revisions to the SCC estimates.

(2) Concerns with the selected scenarios, including potential inconsistencies with other aspects of the modeling

A number of commenters felt the explanation of the selected socio-economic and emissions scenarios was inadequate in both the 2010 and 2013 TSDs and highlighted potential inconsistencies between the GDP, population, emissions, and non-CO_2 radiative forcing trajectories, and in their application to the SCC estimates. For example, one commenter suggested that a better rationale is needed for the choice of the scenarios from the EMF exercise. Other commenters suggested that the scenario assuming immediate and substantial global mitigation efforts is an implausible BAU scenario. Similarly, another commenter suggested that policy scenarios are not appropriate for SCC estimation because using emission scenarios that assume future abatement and mitigation efforts may introduce a downward bias when using the SCC as a benchmark for evaluating the very abatement and mitigation efforts that are assumed to be in place in the future. Other commenters suggested that extrapolation of the scenario variables from 2100 to 2300 may not have properly accounted for correlations among the variables; one commenter noted that work is underway to extend the AR5 SSPs out to 2300 along the extended RCPs and that use of such scenarios may improve consistency of the scenarios past 2100. Commenters also noted that treating certain variables as exogenous to the IAMs might introduce inconsistences if other relevant variables or assumptions differ between the models used to develop the scenarios and the IAMs using them as inputs to estimate the SCC. Other commenters suggested that the average annual global GDP per capita growth rate in the scenarios is too high compared with long term historic growth rates observed in the United States, and that the IWG should have rejected the EMF scenarios because the EMF exercise is not part of a public process and the EMF scenarios are "extreme outliers" relative to recent Energy Information Administration forecasts.

Response

The rationale for using the EMF-22 scenarios is explained in the 2010 TSD. In addition to the fact that they were recent, peer-reviewed, and publicly available, they had the key advantage that GDP, population, and emissions trajectories are internally consistent for each model and scenario evaluated. As noted in the 2010 TSD, the scenarios used "span a wide range, from the more optimistic (e.g. abundant low-cost, low-carbon energy) to more pessimistic (e.g. constraints on the availability of nuclear and renewables)."

Regarding the inclusion of a scenario associated with stabilization of atmospheric concentrations of GHGs at 550 ppm CO_2-e, the 2010 TSD clearly notes that this is "not derived from an assessment of what policy is optimal from a benefit-cost standpoint. Rather, it is indicative of one possible future outcome." As noted above, OMB guidance in Circular A-4 states that the correct baseline for regulatory impact analysis is an agency's best assessment of the state of the world without the regulation, and specifically states that this may include the potential for new domestic and foreign policies that would occur absent the regulation. Including a scenario representative of future mitigation actions is consistent with this guidance, as long as those future policy actions are expected to occur with or without the regulation under examination. As explained in the 2010 TSD, the IWG aimed to select scenarios that span most of the plausible range of outcomes for the socioeconomic variables. Given the level of uncertainty in these trajectories, the IWG felt that it was appropriate to consider a trajectory with significant global mitigation, assuming that this is a distinct possibility even in the absence of U.S. actions. Because there were five scenarios, and each received equal weighting, the stabilization scenario received 20% of the total probability weight.

Regarding potential inconsistencies between scenarios and IAMs, given the nature of estimating the SCC and available data/resources, a full harmonization along all possible dimensions of the three IAMs used to estimate the SCC with the four models used to develop the scenarios was not possible. Therefore, the IWG chose to harmonize the models with respect to the scenario variables to which SCC estimates are most sensitive (GDP, population, and emissions) using common techniques in the literature. The scenarios used were developed by highly respected international modeling groups and published in the peer-reviewed literature. In terms of potential inconsistencies across scenario variables past 2100, an effort was made to account for some basic correlations among scenario variables in the post-2100 extrapolation. For example, extrapolations were based on GDP per capita growth, which implicitly correlates population and GDP growth, rather than GDP levels or growth alone. Similarly, extrapolations were based on CO_2 emissions intensity with respect to GDP, which correlates emissions and GDP growth, rather than CO_2 emissions levels or growth alone.

Consistent with historical observations, it is expected that growth rates of rapidly developing economies will exceed those of already developed economies in the near term. Scenarios with projections of global economic growth that exceed recent trends in developed economies are consistent with this expectation.

The chosen scenarios capture a wide range of potential future states of the world, but were not intended to represent a comprehensive accounting of the full range of uncertainty, and therefore it is possible that future outcomes will fall outside of this range. The IWG acknowledges that the projection of the scenarios beyond 2100 has greater uncertainty than shorter-term projections and will continue to monitor the literature, including the development of extended RCP/SSP scenarios, for ways to improve the estimated trajectories and improve internal consistency.

(3) Future updates should include a formal uncertainty analysis of socio-economic and emissions scenarios.

Multiple commenters noted that the SCC estimates are not based on a detailed accounting of uncertainty over future socioeconomic and emissions conditions, and suggested that in future updates, the estimates should more formally address such uncertainty. It was also suggested that the equal weighting of the five selected scenarios might be inconsistent with their actual probabilities; for example, some commenters felt that given current policies the scenario leading to stabilization of atmospheric GHG concentrations at 550 ppm CO_2-e by 2100 is unlikely to have the same probability as the four BAU scenarios

Response

The IWG acknowledges that the SCC estimates do not include a formal, probabilistic assessment of uncertainty. Rather, the IWG attempted to span a reasonable range of uncertainty by including a range of estimates for key input variables, including climate sensitivity, socioeconomic trajectories, and discount rates. As noted in the 2010 TSD, the IWG considered formally assigning probability weights to different socioeconomic scenarios, but this proved challenging to do in an analytically rigorous way given the dearth of information on the likelihood of a full range of future socioeconomic pathways. In this situation, the IWG determined that, because no basis for assigning differential weights was available, the most transparent way to present a range of uncertainty was simply to weight each of the five scenarios equally for the consolidated estimates. The TSD also presented the results for each scenario separately, to show how the SCC estimates varied across the scenarios.

The IWG will continue to follow and evaluate the latest science on incorporating formal uncertainty analysis over socioeconomic-emissions scenarios, and will seek external expert advice on the technical merits and challenges of potential approaches to incorporate scenario uncertainty in future revisions to the SCC estimates.

5 Discount Rates

Numerous commenters discussed the discount rates used to estimate the SCC. Their comments can be grouped into three main categories: it would be appropriate to include a 7 percent discount rate in the range used to estimate the SCC; the central SCC estimate should be based on a discount rate lower than

3 percent or on a rate that declines over time; and a Ramsey framework should be used to endogenously determine the discount rates.

(1) It would be appropriate to include a 7 percent discount rate in the range used to estimate the SCC.

Most commenters who made this comment cited OMB's Circular A-4, which identifies 3 percent and 7 percent as appropriate discount rates for regulatory impact analysis conducted pursuant to Executive Order 12866. A few commenters offered more specific rationales for using a higher discount rate. One commenter noted that in the United States market interest rates of around 7 percent per year have typically been associated with per capita GDP growth rates of around 1.5 percent per year, and the socio-economic scenarios used in estimating the SCC assume per capita GDP growth rates at least this high. Another commenter noted that low discount rates place relatively more weight on outcomes further in the future, which are more uncertain than near term outcomes. Several commenters indicated that a 7 percent discount rate is appropriate because it represents a better estimate of the opportunity cost of capital investments that would be displaced under compliance with a potential regulation to mitigate CO_2 emissions.

Response

OMB guidance in Circular A-4 recommends that discount rates of 3 percent and 7 percent be used in regulatory impact analysis. The 7 percent rate is an estimate of the average before-tax real rate of return to private capital in the U.S. economy. It is a broad measure that reflects the returns to real estate and small business and corporate capital and is meant to approximate the opportunity cost of capital in the United States. The 3 percent rate is an estimate of the real rate at which consumers discount future consumption flows to their present value, often referred to as the social rate of time preference or the consumption rate of interest. As stated in the 2010 TSD, in a market with no distortions, the return to savings would equal the private return on investment, and the market rate of interest would be the appropriate choice for the social discount rate. In the real world, however, risk, taxes, and other market imperfections drive a wedge between the risk-free rate of return on capital and the consumption rate of interest.

While most regulatory impact analysis is conducted over a time frame in the range of 20 to 50 years, OMB guidance in Circular A-4 recognizes that special ethical considerations arise when comparing benefits and costs across generations. Although most people demonstrate time preference in their own consumption behavior, it may not be appropriate for society to demonstrate a similar preference when deciding between the well-being of current and future generations. Future citizens who are affected by such choices cannot take part in making them, and today's society must act with some consideration of their interest. Even in an intergenerational context, however, it would still be correct to discount future costs and benefits generally (though perhaps at a lower rate than for intragenerational analysis), due to the expectation that future generations will be wealthier and thus will value a marginal dollar of benefits or costs less than the current generation. Therefore, it is appropriate to discount future benefits and costs relative to current benefits and costs, even if the welfare of future generations is not being discounted. Estimates of the discount rate appropriate in this case, from the 1990s, ranged from 1 to 3 percent. After reviewing those considerations, Circular A-4 states that if a rule will have important intergenerational benefits or costs, agencies should consider a further sensitivity analysis using a lower but positive discount rate in addition to calculating net benefits using discount rates of 3 and 7 percent.

The IWG examined the economics literature and concluded that the consumption rate of interest is the correct concept to use in evaluating the net social costs of a marginal change in CO_2 emissions, as the impacts of climate change are measured in consumption-equivalent units in the three IAMs used to estimate the SCC. This is consistent with OMB's guidance in Circular A-4, which states that when a regulation is expected to primarily affect private consumption—for instance, via higher prices for goods and services--it is appropriate to use the consumption rate of interest to reflect how private individuals trade-off current and future consumption.

As explained in the 2010 TSD, after a thorough review of the discounting literature, the IWG chose to use three discount rates to span a plausible range of constant discount rates: 2.5, 3, and 5 percent per year. The central value, 3 percent, is consistent with estimates provided in the economics literature and OMB's Circular A-4 guidance for the consumption rate of interest. The upper value of 5 percent represents the possibility that climate damages are positively correlated with market returns, which would suggest a rate higher than the risk-free rate of 3 percent. Additionally, this discount rate may be justified by the high interest rates that many consumers use to smooth consumption across periods. The low value, 2.5 percent, is included to incorporate the concern that interest rates are highly uncertain over time. It represents the average rate after adjusting for uncertainty using a mean-reverting and random walk approach as described in Newell and Pizer (2003), starting at a discount rate of 3 percent. Further, a rate below the riskless rate would be justified if climate investments are negatively correlated with the overall market rate of return. Use of this lower value also responds to the ethical concerns discussed above regarding intergenerational discounting.

The IWG recognizes that disagreement remains in the academic literature over the appropriate discount rate to use for regulatory analysis of actions with significant intergenerational impacts, such as CO_2 emissions changes that affect the global climate on long time scales. The IWG will continue to follow and evaluate the latest science on intergenerational discounting and seek external expert advice on issues related to discounting in the context of climate change.

(2) The central SCC estimate should be based on a discount rate lower than 3 percent or a rate that declines over time.

Several commenters noted that uncertainty about future economic growth rates implies that future benefits and costs should be discounted to the present at a rate lower than what would be appropriate in the absence of uncertainty. Some comments also recommended that the pure rate of time preference, one component of the discount rate, be set to zero to ensure that the welfare of all generations is given equal weight in the analysis. One commenter suggested that expected future benefits and costs should be discounted at a rate that is the sum of two components: the risk-free rate of return, which is typically associated with the interest rate on short-term government bonds, and a "risk premium" based on the correlation between the benefits of the policy and the growth rate of the broader economy (including both market and non-market goods and services). Some commenters indicated that lower discount rates should be used as a sort of hedge against the risk of "climate catastrophes." Other commenters recommended a declining discount rate; they emphasized discount rate uncertainty and cited research by Weitzman (2001), Newell and Pizer (2003), and Arrow et al. (2013) on this topic, noting that these studies show that under persistent uncertainty about the discount rate, and/or economic growth, the maximization of expected net present value implies a discount rate that declines over time.

Response

As noted above, the IWG selected a range of discount rates from 2.5 to 5 percent; a review of the literature and the reasoning that led to the selection of this range are discussed in detail in the 2010 TSD. Several of the issues raised by commenters were explicitly considered and were part of the rationale for the selected range.

The TSD discusses both descriptive and prescriptive approaches to selecting discount rates. A descriptive approach reflects a positive (non-normative) perspective based on observations of people's actual choices (e.g., savings versus consumption and allocation of savings over more and less risky investments). The prescriptive approach adds a normative component and incorporates judgments that decision makers believe should be reflected in the policy choices that the discount rate is intended to inform. For example, some have argued on ethical grounds that in the Ramsey formula—which dissects market rates into three components, the pure rate of time preference (ρ), growth rate of per-capita consumption (g), and coefficient of relative risk aversion (η)—the ρ component should be set to zero so that the welfare of all generations is valued equally. After considering a range of plausible values from the literature for g and η, the IWG concluded that setting a very low ρ (e.g., 0.1 percent per year) could yield rates in the range of 1.4 to 3.1 percent.

The TSD also discussed uncertainty and its effects on discount rates. The certainty equivalent values of the future benefits of reducing current CO_2 emissions will be lower than the expected value if the benefits and future consumption are positively correlated, assuming people are risk averse on average. This in turn implies that when discounting expected future benefits a discount rate that accounts for uncertainty should exceed a riskless rate. As explained in the TSD, this consideration was part of the logic for setting the upper end of the selected range at 5 percent.

The IWG also considered the issue of "climate catastrophes." To the extent that such outcomes may not be adequately represented in the IAMs, the central tendency estimates from these models may not capture the full range of potential damages from CO_2 emissions. For this reason, in addition to the three mean SCC estimates using discount rates of 2.5, 3 and 5 percent, the IWG recommended including a rate based on the 95th percentile damage estimate (with a 3 percent discount rate) for the upper end of the range of plausible SCC estimates.

Finally, with respect to declining discount rates, the IWG agrees that this is an important area of emerging research. However, no widely-accepted declining discount rate schedule has yet been developed. Some key technical issues warrant careful consideration before adopting a declining discount rate schedule, such as determining how to update the discount rate schedule as uncertainty is resolved over time and ensuring that the use of declining discount rates does not lead to the possibility of time-inconsistent choices. A recent workshop sponsored by the federal government resulted in a paper in *Science* authored by thirteen prominent economists who concluded that a declining discount rate would be appropriate to analyze impacts that occur far into the future (Arrow et al., 2013). However, additional research and analysis is still needed to develop a methodology for implementing a declining discount rate and to understand the implications of applying these theoretical lessons in practice. The IWG will continue to follow and evaluate the latest science on the use of declining discount rates in intergenerational contexts and seek external expert advice on issues related to discounting in the context of climate change.

(3) A Ramsey framework should be used to determine the discount rates.

Some commenters supported use of a Ramsey framework for determining discount rates and noted that the original developers of the IAMs used by the IWG routinely use a Ramsey framework in their own applications of their models. A Ramsey framework, derived from a representative agent who maximizes the sum of discounted utility under specific assumptions, relates the consumption discount rate to the elasticity of the marginal utility of consumption, the growth rate of per capita consumption, and the pure rate of time preference. Some commenters also stated that the socioeconomic scenarios used to calculate the SCC imply growth rates of per capita consumption that change over time, so under the Ramsey framework the discount rates also should change endogenously over time based on the economic growth rates assumed in the underlying socio-economic scenarios.

Response

The IWG agrees that a Ramsey framework can be useful in informing the selection of an appropriate range of discount rates for estimating the SCC. As noted above, this was one of the approaches considered by the IWG in the selection of the 2.5, 3, and 5 percent range.

The IWG considered this framework explicitly in exploring the implications of setting the ρ term (pure rate of time preference) at or near zero to give equal weight to the welfare of all future generations. As explained above, this analysis was part of the basis for selecting the lower end of the range. However, after reviewing several approaches to estimating specific parameters, the IWG noted that there is no consensus in the literature on the appropriate approach for selecting specific values for the components of the Ramsey equation. For this reason, the IWG used this analysis to inform its choice of a range of discount rates, but concluded that the Ramsey equation alone should not determine a specific choice of discount rate.

The IWG agrees that the Ramsey framework could, in theory, support a formulation where discount rates change over time. In a paper summarizing the aforementioned workshop on discounting, thirteen prominent economists indicated that the Ramsey framework “provides a useful framework for thinking about intergenerational discounting” but also pointed out that there is disagreement in the literature about what individual parameters in the Ramsey framework represent (η, in particular), which makes it difficult to select defensible values (Arrow et al., 2012). As noted above, the IWG believes it is premature to use the Ramsey framework as the sole basis for deriving discount rates, either fixed or variable, but did consider the Ramsey literature in deriving the range of 2.5 to 5 percent for use in estimating the SCC. The IWG will continue to evaluate new research on the Ramsey framework and its applicability to SCC estimation and seek external expert advice on issues related to discounting in the context of climate change.

6 Aggregation of Results and Selection of Final Estimates

A number of comments are related to the aggregation of model results and the selection of the final range of SCC estimates. These comments can be grouped into three main categories: concerns with averaging of SCC estimates, the use of means rather than medians as a measure for the central tendency of the SCC estimates, and the use of low and high end estimates in regulatory analyses.

(1) Concerns with averaging of SCC estimates

Some commenters were concerned that pooling the SCC estimates across scenarios and models ignores variability and uncertainties in the estimates. While one commenter explicitly stated that the IWG synthesized model outputs appropriately, several other commenters expressed concern that pooling the results across models and scenarios masks significant differences between models and inappropriately implies that the "true" value of the SCC falls within the range of estimates calculated by the three models. One commenter argued that pooling the results across models and scenarios should be abandoned given the uncertainty around the factors that drive the estimates.

Response

Both the 2010 TSD and the 2013 TSD update present information about the full distribution of SCC estimates within and across possible combinations of the three models and five socioeconomic-emissions scenarios, for each of three discount rates (45 combinations in total) (see tables A2-A4 in Appendix A of the TSDs). Additional summary statistics for the distributions of the SCC estimates are also provided for each of the three models (see Table A5 in Appendix A). The IWG believes that the information presented in the TSDs is sufficiently disaggregated to reflect the variability of the SCC estimates across models, input assumptions, and discount rates. In addition, the IWG has provided the full set of Monte Carlo modeling results (10,000 model runs for each combination, for a total of 450,000 observations per emissions year) to outside researchers upon request and will continue to do so.

As discussed in the 2010 TSD, using the full distribution of the SCC estimates from the 45 scenarios would be impractical in a regulatory impact analysis. To produce a range of plausible estimates that still reflects the uncertainty about the SCC estimates, the results from the various model and scenario combinations (150,000 observations per emissions year for each of the three discount rates) were pooled to produce three separate probability distributions for the SCC for emissions in a given year, one for each assumed discount rate (2.5, 3 and 5 percent). Three point estimates were then derived from these pooled distributions representing the mean at each discount rate. The IWG considers this approach for presenting expected SCC values across a range of discount rates to be appropriate for representing the central tendency of the SCC estimates across scenarios. The fourth value, the 95th percentile of the pooled distribution using a 3 percent discount rate, is included to represent higher-than-expected economic impacts from climate change further out in the tail of the SCC distribution - i.e., impacts that may have lower probability of occurring but relatively high damages. For purposes of representing the uncertainties involved, the TSDs emphasized the importance of considering and presenting the full range of these four estimates in regulatory impact analysis.

The IWG agrees that the modeling of uncertainty in our analysis, including the uncertainty explicitly represented in the IAMs, may not capture the full range of uncertainty of the "true" value of the SCC. This concern is common to most quantitative assessments of uncertainty. By definition, the modeling of uncertainty requires a model, and therefore cannot capture the uncertainty associated with model selection. However, the IWG does not agree that pooling results across models implies that the estimates capture the full range of uncertainty, nor did the IWG make such a claim in the TSDs. Rather, the IWG attempted to capture a reasonable range of uncertainty using information available in the peer-reviewed literature and the uncertainty analysis built into the models themselves. Using three models rather than one helps address, but does not eliminate, uncertainty associated with model choice.

(2) Use of means rather than medians as a measure of the central tendency of the SCC estimates

A few commenters suggested that the median of the distribution of SCC estimates rather than the mean, as used by the IWG, would be a more appropriate measure of the central tendency of the SCC estimates. Another commenter suggested using both the mean and the median, along with presenting other distributional information (e.g., variances, low and high end percentile estimates, and other characteristics of distributions).

Response

The choice of the mean or the median as a measure of central tendency depends on the context. In skewed distributions, such as for the SCC estimates, the median will often give a more "typical" outcome, while the mean will give full weight to the tails of the distribution. In some cases, the typical outcome is of most interest. For example, in describing household incomes the median is most often used because the focus is on understanding the income of the typical household, and using the mean might distort this picture by giving undue weight to a small number of very wealthy households. In the climate change context, however, sound decision-making requires consideration of not only the typical or most likely outcomes, but also less likely outcomes that could have very large (or small, or even negative) damages (the tails of the distribution). Use of the median to represent the SCC in a regulatory impact analysis would not necessarily lead to the most efficient policy choice that uses resources wisely to mitigate potential climate impacts (e.g., maximize the expected net benefits). In this case, the IWG believes that the mean is the appropriate measure of central tendency.

(3) Use of low and high end estimates in regulatory analyses

Several commenters suggested that both lower and upper end estimates should be part of the final range of estimates used in regulatory analyses. Specifically, they believe the range should include a 5th percentile estimate, in addition to the 95th percentile estimate from the pooled distribution using the 3 percent discount rate. In contrast, one commenter suggested that, because the models do not presently account for high-end risks, RIAs should compensate by using only the most conservative estimates reported by the IWG (i.e., the 95th percentile estimate using the 3 percent discount rate). Another commenter similarly suggested using only the worst case (highest) estimate out of all the simulation results in place of the mean estimate.

Response

Along with the four selected SCC estimates for each emissions year, the IWG presented more detailed information about the full distribution of SCC estimates for emissions in the year 2020. Specifically, the 2013 TSD reports information on the full distribution of the SCC estimates for emissions in year 2020 for each model, scenario, and discount rate combination , including the low-end percentiles (i.e., 1st, 5th and 10th percentiles).[11] In addition, as noted above, complete distributions for all emissions years are available upon request. While the IWG did not present a summary 5th percentile estimate (i.e., pooling results across the models and scenarios) for use in regulatory impact analysis, for reasons discussed below, the model and scenario specific statistics for 2020 provide a general sense of how the 5th percentile relates to the mean. Furthermore, as we note above the IWG has provided the full set of Monte Carlo modeling results to outside researchers upon request and will continue to do so. This information may be used to calculate a full set of 5th percentile summary statistics that are comparable to the 95th percentile estimates provided in the TSDs.

As the 2010 TSD discusses, the SCC estimates derived from the three integrated assessment models have several significant limitations that could lead to a substantial underestimation of the SCC. These limitations include the incomplete treatment and monetization of non-catastrophic damages, the incomplete treatment of potential “catastrophic” damages, and uncertainty in extrapolation of damages to high temperatures. The IPCC Fourth Assessment Report, which was the most current IPCC assessment available at the time of the IWG’s 2009-2010 review, discussed these limitations and concluded that it was “very likely that [SCC] underestimates” climate change damages. Based on the current scientific understanding of climate change and its impacts, and on the limitations of the IAMs in quantifying and monetizing the full array of potential “catastrophic” and non-catastrophic damages, the IWG concluded that the distribution of SCC estimates may be biased downwards. Since then, the peer-reviewed literature has continued to support this conclusion. For example, the IPCC Fifth Assessment report observed that SCC estimates continue to omit various impacts that would likely increase damages. The 95th percentile estimate was included in the recommended range for regulatory impact analysis to address these concerns.

In addition, as acknowledged in the 2010 TSD, the SCC estimates derived from the three IAMs did not take into consideration the possibility of risk aversion. That is, individuals may have a higher willingness-to-pay to reduce the likelihood of low-probability, high-impact damages than they do to reduce the likelihood of higher-probability, lower-impact damages with the same expected cost. The inclusion of the 95th

[11] The 2010 TSD including information on the full distribution of SCC estimates for the emission year 2010, however the 2013 TSD presented this information for the 2020 emissions year as 2010 was then a historical year.

percentile estimate in the SCC values was also motivated by this concern. In contrast, the IWG is not aware of systematic upward biases in the estimates comparable to the downward biases discussed above. For this reason, while the IWG has been fully transparent regarding the entire range of uncertainty reflected in the probability distributions, we did not include a 5^{th} percentile estimate in the selected range for regulatory impact analysis.

Regarding the suggestion that only the high end of the range or worst-case scenario should be used in regulatory cost-benefit analysis, the IWG disagrees. The recommended range represents the central tendency of SCC estimates across three reasonable discount rates, plus a high-end estimate to account for missing damage categories and “catastrophic” outcomes. It is the judgment of the IWG that this approach will best inform decision makers and the public about both the range of “likely” damages and the possibility that actual damages could be much higher.

7 Consideration of Uncertainty

The IWG received a number of comments on the analyses and presentation of uncertainty in the TSD, as well as comments regarding the implications of uncertainty for the use of the SCC estimates in regulatory impact analysis.

(1) Analysis and presentation of uncertainty

Several commenters suggested that the IWG was rigorous in addressing uncertainty by conducting Monte Carlo simulations with the IAMs to estimate distributions of the SCC over probabilistic specifications of the equilibrium climate sensitivity and other uncertain parameters as identified by the model developers. Other commenters suggested that key uncertainties merit further exploration and discussion in the TSD. Several commenters recommended that additional uncertainty analysis be conducted on key aspects of the modeling, such as assumptions regarding the carbon cycle, physical responses to climate change, technological change, adaptation, and post-2100 extrapolations of the socioeconomic-emission scenarios, among others. One commenter called for a separate section in the TSD that identifies key sources of uncertainty, along with a qualitative assessment of the impact those key uncertainties have on the SCC estimates, and to the extent feasible, a quantitative assessment as well. Some commenters suggested that the references in the 2013 TSD to discussions of uncertainty in the 2010 TSD are inadequate and make it difficult for the reader to understand the uncertainty associated with the revised estimates. One commenter questioned whether the IWG reported too many significant digits given the degree of uncertainty about the estimates. Several commenters also suggested that it would be appropriate to shorten the modeling time horizon due to the uncertainty associated with projecting impacts out to 2300. Two commenters suggested a time horizon of 2100 to be consistent with the time horizon considered in IPCC assessment reports. In addition, several commenters requested that additional graphical information be presented, and electronic copies of the results be made publically available.

Response

The IWG agrees with the comments that supported the rigor of its uncertainty analysis. Uncertainty is inherent in all regulatory impact analysis. It is especially salient in regards to the SCC estimates because of their broad spatial and temporal dimensions. In addition to conducting Monte Carlo analysis for a subset of key parameters, the IWG included extensive discussion of uncertainty in the TSDs, and the documentation for the individual IAMs themselves contains additional discussion of the assumptions and uncertainties in the models. The 2010 TSD and the updated 2013 TSD provided visual depictions of the distributions of the SCC estimates in addition to detailed statistics including percentiles and higher order moments. In addition to the extensive information provided in the TSDs, the IWG has provided the full range of model results to outside researchers upon request and will continue to do so.

The IWG also agrees that the trajectory of socioeconomic-emission scenarios beyond 2100 is uncertain. However, as the 2010 TSD notes, because of the long atmospheric lifetime of CO_2, using too short a time horizon could miss a significant fraction of damages under certain assumptions about the growth of marginal damages. Therefore, the IWG ran each model through 2300. The IWG will continue to follow and evaluate the scientific literature on long-term scenario development.

The IWG reported SCC estimates out to one decimal place (i.e., at least two significant digits) in the 2010 TSD and to the nearest dollar in the 2013 TSD (i.e., two or three significant digits, depending on the year and discount rate/statistic). The IWG chose not to use decimal places in the 2013 TSD to avoid the impression of artificial precision but will also explore presentation with a consistent number of significant digits. The IWG welcomes the recommendations to strengthen the characterization of uncertainty and plans to seek external expert advice on the technical merits and challenges of potential approaches to improve the characterization and analysis of uncertainty in future updates.

(2) Implications of uncertainty for the use of the SCC estimates in regulatory impact analysis

Some commenters suggested the degree of uncertainty in the SCC estimates makes them too speculative for use in regulatory analysis. These commenters argued that SCC is an unknown quantity and cannot be discerned in meteorological or economic data going back a century or more. Some commenters suggested that if non-validated climate parameters, arbitrary damage functions, or below-market discount rates were used, analysts could produce almost any result they desire. Another commenter suggested that the large variance associated with the distributions of the SCC estimates relative to the mean indicates that the estimates are not of sufficient precision to be informative in regulatory analysis. In contrast, other commenters stated that uncertainty in benefits estimates does not mean they should be excluded from regulatory impact analyses. These commenters pointed out that no benefit or cost estimate is certain and both court decisions and executive orders dating back to 1981 have recognized this. To address this, agencies have been directed to use best available estimates and acknowledge uncertainties, which they suggested is appropriately done in the TSDs.

Response

All regulatory impact analysis involves uncertainty. The IWG acknowledges uncertainty in the SCC estimates but disagrees that the uncertainty is so great as to undermine use of the SCC estimates in regulatory impact analysis. The uncertainty in the SCC estimates is fully acknowledged and comprehensively discussed in the TSDs and supporting academic literature. While uncertainty must be acknowledged and addressed in regulatory impact analyses, even an uncertain analysis provides useful information to decision makers and the public. For example, if an analysis shows that benefits of a policy option consistently do (or do not) justify costs even over a broad range of estimates, this may increase confidence in the robustness of this conclusion. Conversely, if choices among parameter estimates within a plausible range significantly affect the conclusions of the analysis, this is an important consideration in deciding how to weigh the analytical results in the decision making process. The presence of uncertainty is thus not a reason to exclude the best available estimates of quantified/monetized benefits, as long as it is appropriately characterized. Rather, good regulatory practice requires that agencies use the best available scientific, technical and economic information to derive the best estimates of costs and benefits that they can, and then communicate to the public the limitations and uncertainties of the analyses. This is what the IWG has attempted to do in developing and discussing the SCC estimates. As noted in the TSDs, the IWG is committed to periodic updates in the estimates to reflect ongoing developments in our understanding of the science and economics of climate change, including the treatment of uncertainty.

8 Use of Global vs. Domestic SCC Estimates

Many commenters discussed the scope of the SCC estimates, and the degree to which damages experienced outside U.S. borders should be considered in domestic regulatory analysis. These comments can be grouped into two main categories: those that felt that the focus on global damage estimates is appropriate, and those that felt that domestic damage estimates received inadequate attention. Responses to these comments are provided below. In addition, many commenters stated that domestic SCC estimates must be used in RIAs to ensure consistency with OMB Circular A-4 requirements. This issue is addressed in Section 10 below.

(1) The focus on global damage estimates is appropriate.

A number of commenters supported the IWG's decision to base the SCC estimates on global damages. Commenters explained that climate change is a global commons problem because carbon pollution does not remain within one country's borders, and that the use of global damages in the SCC is consistent with the economic theory of the commons. One commenter further stated that if damage estimates are limited to only those within each country's borders, any actions based on those estimates would lead to a collective failure to optimally mitigate GHG emissions. Another commenter referred to the importance of this effect by stating that the consideration of global damages in domestic rulemaking can be based on an expectation of reciprocity from other countries. Several commenters stressed the importance of the use of global SCC estimates as a tool in international negotiations. Finally, some commenters offered other reasons for considering damages in regions outside of the United States, including liability, national security concerns, trade-related "spillover effects", and the principle in international environmental law of reducing cross-border harm.

Response

The IWG agrees that a focus on global SCC estimates in RIAs is appropriate. As discussed in the 2010 TSD, the IWG determined that a global measure of SCC is appropriate in this context because emissions of most greenhouse gases contribute to damages around the world and the world's economies are now highly interconnected. To reflect the global nature of the problem, the SCC incorporates the full damages caused by CO_2 emissions and we expect other governments to consider the global consequences of their greenhouse gas emissions when setting their own domestic policies.

The IWG also agrees that if all countries acted independently to set policies based only on the domestic costs and benefits of carbon emissions, it would lead to an economically inefficient level of emissions reductions which could be harmful to all countries, including the United States, because each country would be underestimating the full value of its own reductions. This is a classic public goods problem because each country's reductions benefit everyone else and no country can be excluded from enjoying the benefits of other countries' reductions, even if it provides no reductions itself. In this situation, the only way to achieve an economically efficient level of emissions reductions is for countries to cooperate in providing mutually beneficial reductions beyond the level that would be justified only by their own domestic benefits. By adopting a global estimate of the SCC, the U.S. government can signal its leadership in this effort. In reference to the public good nature of mitigation and its role in foreign relations, thirteen prominent academics noted that these "are compelling reasons to focus on a global SCC" in a recent article on the SCC (Pizer et al., 2014). In addition, as noted by commenters, there is no bright line between domestic and global damages. Adverse impacts on other countries can have spillover effects on the United States, particularly in the areas of national security, international trade, public health and humanitarian concerns.

(2) Domestic damage estimates receive inadequate attention.

A number of commenters suggested that the use of global damages creates a mismatch between estimates of costs and benefits in agency RIAs. Use of a global rather than domestic SCC may overstate the net benefits to the United States of reducing emissions, because global benefits are compared to domestic costs. A policy that appears cost-justified from a global perspective may not be from a purely domestic U.S. perspective. Therefore, these commenters suggest that a global SCC is only appropriate when the analysis considers global costs and benefits in the context of a global carbon mitigation program.

Other commenters indicated that the IWG should update and report domestic climate damages separately from global estimates for several reasons, including the public's right to know the domestic benefits of domestic regulatory actions. A few comments stated that the IWG should more clearly articulate that the SCC includes global damages, which they felt was particularly unclear in the 2013 TSD.

Finally, commenters also addressed the provisional range of domestic damages that was presented in the 2010 TSD. Several comments stated that the range discussed in the 2010 TSD for the domestic SCC was too high. Two commenters suggested a range for the domestic share of total global damages of 6 to 8.7 percent based on a paper by Nordhaus (2011). One commenter stated that the methods used to estimate the domestic damages as 7 to 23 percent of global damages is too speculative for quantification of the SCC.

Response

As stated in the prior section, GHG emissions in the United States will have impacts abroad, some of which may, in turn, affect the United States. For this reason, a purely domestic measure is likely to understate actual impacts to the United States. Also, as stated above, the IWG believes that accounting for global benefits can encourage reciprocal action by other nations, leading ultimately to international cooperation that increases both global and U.S. net benefits relative to what could be achieved if each nation considered only its own domestic costs and benefits when determining its climate policies.

Further, as explained in the 2010 TSD, from a technical perspective, the development of a domestic SCC was greatly complicated by the relatively few region- or country-specific estimates of the SCC in the literature, and impacts beyond our borders have spillover effects on the United States, particularly in the areas of national security, international trade, and public health. As a result, it was only possible to include an “approximate, provisional, and highly speculative” range of 7 to 23 percent for the share of domestic benefits in the 2010 TSD. This range was based on two strands of evidence: direct domestic estimates resulting from the FUND model, and an alternative approach under which the fraction of GDP lost due to climate change is assumed to be similar across countries. We note that the estimated U.S. share of global damages based on the Nordhaus (2011) study cited by several commenters largely falls within the provisional range offered in the 2010 TSD.

In conclusion, the IWG believes that the only way to achieve an efficient allocation of resources for emissions reduction on a global basis is for all countries to base their policies on global estimates of damages and will therefore continue to recommend the use of global SCC estimates in regulatory impact analyses. The IWG will also continue to review developments in the literature, including more robust methodologies for estimating SCC values based on purely domestic damages, and explore ways to better inform the public of the full range of carbon impacts, both global and domestic.

9 Other Comments

Other comments include those related to “leakage” and valuation of changes in non-CO2 GHG emissions.

(1) CO_2 emissions “leakage”

Several commenters suggested that the methods used to estimate climate damages should account for "leakage" of emissions in the quantification of the SCC. Specifically, commenters suggested that in cases where a new regulation increases domestic operating costs and causes industrial activity to shift to jurisdictions with less stringent regulations, net GHG emissions could fall less than predicted, or even increase. In these cases, the actual emissions reduction would be lower than indicated in a simple analysis. Commenters suggested that this effect be addressed either by the provision of additional guidance to agencies conducting RIAs, or in the estimated SCC value itself by adjusting estimated climate damages to account for it.

Response

The IWG agrees that this is an important issue for analysts to consider in determining the net CO_2 reductions to be valued in an RIA. However, this does not affect the calculation of the SCC itself, which is an estimate of the marginal benefit of a net one-ton reduction in CO_2 emissions. The SCC estimates are multiplied by estimates of net GHG emissions changes to calculate the value of benefits associated with a policy action in a given year. It is in the estimation of net GHG emissions, and not the SCC, that any leakage should be accounted for.

(2) Valuation of changes in non-CO_2 GHG emissions

Several commenters recommended that estimates be developed for valuing changes in the emissions of other greenhouse gases, such as methane, HFCs, and black carbon, as soon as possible. One commenter specified that the direct modeling approach for estimating the social cost of methane is preferable, but even an approximation approach (e.g., based on the use of the global warming potential (GWP) gas comparison metric) has merit and would be better than no estimate. The commenter asserted that the failure to set a social cost of methane estimate has the effect of eliminating any benefit of methane reductions from regulatory consideration and such a failure is arbitrary and capricious. Another commenter advocated for the use of both 100 and 20-year GWPs for converting non-CO_2 GHG emission changes into CO_2 equivalents before applying the SCC estimates.

Response

The IWG recognizes the importance of quantifying and monetizing the benefits of regulations to the extent feasible, and discussing qualitatively any benefits that cannot be quantified. The IWG does not agree that benefits that are not monetized are eliminated from regulatory consideration. On the contrary, most RIAs include discussion of non-quantified benefits and these may be an important factor in decision-making, depending on their projected significance. However, as noted by the commenters, the IWG has not established a methodology for valuing the social cost of other GHGs. In the absence of such estimates, a few recent rulemakings have included sensitivity analyses in which the GWP gas comparison metrics are used to convert non-CO_2 emissions reductions to CO_2 equivalents, which are then valued using the SCC estimates. For example, the 2012 New Source Performance Standards and Amendments to the National Emissions Standards for Hazardous Air Pollutants for the Oil and Natural Gas Industry and the 2017-2025 Light-duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards used this approach in sensitivity analyses.

Although more directly modeled estimates of the climate change benefits of reducing some GHGs (e.g., methane) have been presented in the scientific literature, the methodology behind these estimates differs from the methodology behind the USG SCC estimates. Assessing the strengths and limitations of alternate approaches for estimating economic damages from other GHGs has so far been outside the scope of the IWG's assessment of economic damages from CO_2 emissions, though the 2010 TSD identified this as an area we hope to address in future updates. We also note that a recently published paper (Marten et al., 2014) develops estimates of the social cost of CH_4 and N_2O using a methodology that is intended to be consistent with the IWG estimates of the SCC. The IWG will continue to follow and evaluate the literature on the social cost of non-CO_2 GHGs and the feasibility of developing non-CO_2 social cost estimates.

10 Process Related Comments

Many commenters either voiced support for or criticized particular aspects of the interagency process used to develop the SCC estimates. Process issues raised included legal/statutory authority for issuing the estimates, consistency with applicable OMB guidance documents, transparency, opportunity for public comment, and appropriate use of the estimates.

(1) Legal/statutory authority for issuing the SCC estimates

One group of commenters asserted that the legal basis for using the SCC is clear and well-established. These commenters highlighted the 2007 Ninth Circuit decision that concluded that a National Highways and Transportation Safety Administration rule was arbitrary and capricious for not including a monetized estimate of the SCC. The Court noted that "…while the record shows that there is a range of values, the value of carbon emissions reductions is certainly not zero."

Other commenters argued that OMB's adoption of the SCC estimates is arbitrary, capricious, and contrary to law because OMB requires all Federal agencies to use its SCC estimates without identifying any legal basis or authority for doing so. These commenters argued that because OMB's "promulgation" of the SCC values falls within the APA's broad definition of a rule, OMB must comply with the procedural and substantive requirements laid out in the APA for rulemaking. These commenters further stated that the TSDs do not show a "rational connection between the facts found and the choices made," and that even if the three IAM models themselves were entirely sound, the non-public inputs into those models would render the SCC estimates arbitrary and capricious.

Response

As a preliminary matter, the IWG notes that although the development of the SCC estimates was co-chaired by OMB and CEA, the estimates and supporting TSDs were not issued by OMB, but rather through a consensus based process involving the entire working group.

The IWG agrees with commenters who believe that it has legal authority to develop these estimates, and was cognizant of the Ninth Circuit decision referenced by these commenters when it decided to do so. The IWG does not agree that issuance of the SCC estimates constitutes an APA rule making. The APA definition of a rule is "an agency statement of general or particular applicability and future effect designed to implement, interpret, or prescribe law or policy." The SCC estimates are not designed to implement, interpret, or prescribe law or policy. Rather they are intended to provide guidance to agencies on a science-based methodology for estimating the benefits of CO_2 reductions in regulatory impact analysis.

OMB has long-established authority to oversee the regulatory review process, including preparation of regulatory impact analyses. OMB's authority in this area is contained in Executive Orders 12866 and 13563, among others, and has been acknowledged by Congress in a series of statutes, including the Small Business Regulatory Enforcement and Fairness Act, the Congressional Review Act, the Information Quality Act, and the Regulatory Right to Know Act. It is fully consistent with this authority for OMB to offer guidance to agencies on best practices for conducting regulatory impact analysis, as it did, for example, in issuing Circular A-4. In the present case, OMB determined that it was appropriate to exercise this authority through a consensus-based process involving a broad range of agencies that may issue rules affecting CO_2 emissions.

The TSDs explain in detail the factual and policy basis for all of the various methodological choices involved in developing the SCC estimates. The IAMs are documented in the scientific literature. In addition, the IWG has assisted interested members of the public in obtaining additional information on the workings of the models. It has also provided full technical details of its own use of the models, including output of model runs, to interested parties upon request. However, because the SCC estimates are not a rule, as a legal matter they are not subject to the arbitrary and capricious standard of the APA.

(2) Consistency with OMB guidance documents, including the Information Quality Act guidelines, Peer Review Bulletin, and Circular A-4

Some commenters stated that the process used to develop the SCC estimates did not adhere to the OMB Information Quality Act (IQA) guidelines. The IQA requires federal agencies to take steps to maximize the quality, objectivity, and integrity of the information they disseminate, and to provide a mode of redress to correct flawed or incomplete information. These commenters stated that the SCC estimates are clearly "influential information" under the Guidelines and as such, must be reproducible and transparent with respect to: (1) the source of the utilized data; (2) the various assumptions employed; (3) the analytic methods applied; and (4) the statistical assumptions employed. Some commenters also stated that OMB's response to an IQA petition from a group of trade associations was inadequate and did not provide any information that was not already in the TSDs.

Several commenters focused on peer review in particular. These commenters stated that while peer review of the models themselves is important, it is not sufficient because the model inputs and subsequent manipulation of results (e.g., equal averaging) were not peer reviewed. They believe that the IWG must subject the SCC estimates and methodology to peer review to give the public greater confidence in the results. Some also stated that the IWG should consider model-specific peer review as well. This would consist of a review of each model's theoretical underpinnings and methodologies, as well as their appropriateness to specific applications. These commenters indicated that while specific applications may have been peer reviewed when published in the scientific literature, the models themselves were not.

Additionally, some commenters focused on the degree to which the SCC estimates are consistent with the OMB Circular A-4 guidelines for conducting regulatory impact analysis. These commenters stressed that the selected discount rates do not comply with Circular A-4 and should be selected through an open process including peer review. They noted that while Circular A-4 allows a sensitivity analysis with lower discount rates when a rule will have "important intergenerational benefits or costs," it still requires use of 3 percent and 7 percent. They also indicated that the estimates are not consistent with Circular A-4 guidelines regarding the use of domestic rather than global estimates of regulatory benefits.

Response

The IWG does not agree that the TSDs are inconsistent with the IQ Guidelines. To ensure that the IWG's methodology is transparent, the TSDs are comprehensive and technically rigorous in explaining the sources of data, the assumptions employed, the analytic methods applied, and the statistical assumptions employed. To ensure that the results are reproducible, IWG members have provided technical assistance and modeling results to external stakeholders upon request. Regarding the IQA petition, OMB responded to all of the points raised by petitioners. The fact that OMB's response used some language from the TSDs reflects OMB's judgment that these issues were already addressed in the TSDs themselves.

With regard to peer review, the IWG notes that the assumptions and models employed in generating the SCC estimates are all drawn from the peer-reviewed academic literature. To further strengthen the robustness of the SCC estimate, the IWG plans to seek external expert advice on technical opportunities to improve the SCC estimates in future updates, including many of the approaches suggested by commenters and peer-reviewed literature, and summarized in this document.

Circular A-4 is a living document, which may be updated as appropriate to reflect new developments and unforeseen issues. OMB was fully involved in the development of the SCC estimates as a working group co-chair and supports the working group's recommendations regarding the discount rate and the focus on global damages. The departure from the standard discount rate recommendations in Circular A-4 is explained in detail in the TSDs and in Section 5 of this document. Briefly, the use of 7 percent is not considered appropriate for intergenerational discounting. There is wide support for this view in the academic literature, and it is recognized in Circular A-4 itself. The emphasis on global rather than domestic damages is also explained in detail in the TSDs. Beyond the fact that good methodologies for estimating domestic damages do not currently exist, basing decisions on only the domestic damages from carbon emissions will lead to an inefficient allocation of resources to reducing them, especially if all countries adopt a similarly short-sighted approach. An efficient outcome can only be achieved if all countries consider the full costs and benefits of their actions; the United States continues to be a leader in working to establish such a regime internationally.

(3) Transparency

Several commenters asserted that the process of selecting the models and input assumptions, including much of the basic information underlying these decisions, has been insulated from public scrutiny. Commenters expressed concern that the IWG has not revealed the identity or qualifications of its participants, the role of government contractors, or the details of its internal processes, including the frequency of meetings and the nature of its deliberations. These commenters further suggested that the TSDs discuss only a few selected inputs to the models, which, though important, are not the only important inputs. They believe greater transparency is also needed regarding the models themselves and the key differences among them.

Some commenters also suggested that the discussion in the TSD of the 2013 revisions is insufficient for understanding and interpreting the changes in the SCC estimates. Additional justification for many of the revisions would be helpful (e.g., space heating expenditure reductions, transient temperature responses, constant indirect methane radiative forcing effect, saturation, regional scaling factors, probability of a discontinuity, adaptation, CO_2 absorption, regional climate modeling). Commenters suggested that discussion of uncertainty regarding the revisions would also be helpful. At a minimum, commenters suggested it would be reasonable to explain differences across models for similar components (e.g., sea level rise, transient temperature response, saturation, and adaptation), noting as a source of confusion that the TSDs have references to previous model versions, websites, and working papers, and suggested that a clear citation for each of the revisions in each model would be useful.

Other commenters explicitly noted ways in which they disagreed with the comments above. They indicated that the 2010 TSD sets out in detail the IWG's decision-making process with respect to how it assessed and employed the models, and that the 2013 TSD discusses how the three IAMs used in the analysis were updated in the publically-available academic literature over the three-year interim period by the independent researchers who developed them, and clarifies that the increase in the SCC estimate from 2010 to 2013 resulted solely from updates to the three underlying IAMs.

Response

The IWG believes that its process was inclusive, transparent, and appropriately considered public input. The TSDs fully document the methodology used to develop the estimates and the considerations that led the IWG to adopt this methodology. While the details of the IWG's internal processes were not discussed in the TSDs, this is common for most government (and non-government) documents. Such details were not considered germane to the public's understanding of the SCC estimates and the methodology used to produce them, but a general overview is provided here.

In developing the 2010 estimates, the IWG met frequently in the year preceding the release of the February 2010 TSD. For the 2013 update, only a few meetings were needed because the group decided to make no changes beyond incorporating the most recent versions of the IAMs. The IWG, in particular professional economic staff with modeling expertise, oversaw the primary modeling and calculations for both the 2010 and 2013 SCC estimates using the most recent versions of the three IAMs available at the time. To develop the 2010 estimates, the staff members ran two of the three models and contracted with the developer of the third model to perform those runs. The contractor did not participate in any of the interagency meetings but rather received instructions for how to conduct the model runs (e.g., specification of the three sets of input assumptions as determined by the working group). The staff members ran all three models to develop the 2013 estimates. Decision making for both the 2010 and 2013 processes was by consensus of IWG members. The details of internal discussions are deliberative, but the discussions were generally technical in nature and the issues discussed and conclusions reached are well documented in the TSDs. Regarding the transparency of the underlying models themselves, the IWG notes that they are well documented in the academic literature.

The Government Accountability Office (GAO) recently completed a review of the process used to develop the SCC estimates. GAO concluded that according to IWG participants, all major issues discussed were documented in the TSDs, which is consistent with Federal standards for internal control, and the processes and methods used were based on the principles of (1) consensus-based decision-making, (2) reliance on existing academic literature and modeling, and (3) disclosure of limitations and incorporation of new information through consideration of public comments and revision of the estimates as updated research became available.[12]

IWG members have also assisted individual requestors in obtaining more detailed information about the modeling. For example, one requestor noted publically that IWG "modelers have been very open, collegial, and helpful."[13]

Regarding the explanation in the TSD for the 2013 revisions, no changes were made to the input assumptions developed by the IWG between the 2010 and 2013 estimates. The only changes were those made by the model developers themselves to the underlying models, which are documented in the academic literature. To assist the public in understanding these changes, the 2013 TSD provides a brief summary of the most important ones, as well as references to the relevant literature where more detailed information can be found. As with the 2010 TSD, the IWG did not attempt to evaluate the modeling choices made by the modelers. Rather, by selecting the three "most widely used impact assessment models" (NAS, 2010), the IWG intended to reflect a reasonable range of modeling choices and approaches that collectively reflect the current literature on the estimation of damages from CO_2 emissions. As explained in the 2010 TSD:

> The parameters and assumptions embedded in the three models vary widely. A key objective of the interagency process was to enable a consistent exploration of the three models while respecting the different approaches to quantifying damages taken by the key modelers in the field. An extensive review of the literature was conducted to select three sets of input parameters for these models: climate sensitivity, socio-economic and emissions trajectories, and discount rates…All other model features were left unchanged, relying on the model developers' best estimates and judgments…The sensitivity of the results to other aspects of the models (e.g. the carbon cycle or damage function) is also important to explore in the context of future revisions to the SCC but has not been incorporated into these estimates.

Accordingly, the IWG did not attempt to explain in detail how the damage functions in the models were constructed or their strengths and weaknesses, either for the earlier model versions used in the 2010 estimates or for the updated versions used for the 2013 estimates. Rather, stakeholders who are interested in these details are encouraged to consult the model documentation and the related academic literature referenced in the TSDs, as well as the model developers themselves. The IWG accepts the point that clearer citations to specific model versions and revisions would be helpful and will attempt to address this in the next update of the TSD.

(4) Opportunities for public comment

While some commenters acknowledged that the public has had multiple opportunities to comment on the SCC estimates and TSDs, others felt that the opportunities for public comment have been insufficient. A few of these commenters indicated that the public has not been provided sufficient information and

[12] http://www.gao.gov/products/GAO-14-663
[13] http://dailysignal.com/2013/11/06/white-house-reopens-the-scc/

asked that additional supplemental and supporting documents be made available to the public for comment, including all of the data, models, assumptions, and analyses relied on to arrive at the SCC estimates. They suggested that OMB's responses to FOIA requests implied that there are thousands of pages of supporting documents that have not been released to the public.

Some commenters stated that the continued development of SCC estimates should have strong oversight in both the Executive branch and Congress, that there should be continued opportunities for the public to comment, and that the analysis should be conducted in an open fashion.

Response

The IWG agrees with those commenters who believe the public has had ample opportunities to comment on the SCC estimates and methodology. Opportunity for public comment on all aspects of the SCC estimates was provided on the interim estimates selected by the IWG and in the numerous proposed rules issued by Federal agencies between February 2010 and May 2013 that made use of the estimates. As a general practice, agencies request comments on all aspects of the regulatory impact analysis, thereby providing ample opportunity for the public to comment on SCC estimates used in these analyses. These comments helped inform the IWG's development of the 2013 revised estimates. In addition, OMB provided a stand-alone comment period on the 2013 estimates. This document summarizes the comments received and provides the IWG's response.

Regarding the adequacy of the information provided to the public as a basis for comment, the TSDs provide a complete record of the methodology and assumptions used to develop the SCC estimates, including references to the academic literature. Independent analysts have sought and received information from the IWG allowing them to implement the IWG approach and modify it further if they choose. Additional documentation is available in the academic literature on the IAMs themselves.

With regards to several FOIA requests received by OMB and other IWG members, the only documents withheld were deliberative documents that are protected under applicable FOIA exemptions. Most of these documents were either intermediate drafts of TSD language or e-mails exchanged among IWG participants discussing various aspects of the methodology and results. Such documents are not typically provided in the record of agency actions and are not necessary for informed public comment.

The IWG is committed to providing additional opportunities for public comment when future updates of the SCC are released and agrees that analysis should continue to be conducted in an open fashion.

(5) Use of the SCC Estimates in Regulatory Impact Analysis

In addition to expressing views about how the SCC estimates were derived, many commenters discussed the *application* of the estimates. Some commenters explicitly endorsed the use of the SCC in rulemaking analyses, highlighting that accounting for the economic harms caused by climate change is a critical component of sound benefit-cost analyses of regulations that directly or indirectly affect greenhouse gas emissions. These commenters stated that without an SCC estimate, regulators would by default be using a value of zero for the benefits of reducing carbon pollution, implying that carbon pollution has no costs.

They urged the IWG to continuously update the SCC, as new economic and scientific consensus emerges, in line with the stated intentions of the IWG.

Other commenters disagreed with continued use of SCC estimates based on both process and substance concerns. On the process side, some commenters asserted that the limitations of the process used to generate the estimates (see earlier comments in this section) render them unsuitable for use in regulatory impact analysis and requested that the IWG withdraw the TSDs until these process flaws have been corrected. Issues specifically highlighted in this area were lack of peer review and inadequate opportunity for public comment. Other commenters stated that the SCC estimates are too uncertain for decision making, and several requested that the IWG provide more explicit guidance on when and when not to use them. For example, several commenters said the TSD should explicitly note that the SCC estimates are only for use in benefit-cost analysis of Federal regulations and are not a "price" on carbon or a proxy for the anticipated cost of complying with CO_2 regulations; in addition they should not be used in NEPA environmental impact statements or state level decision making. One commenter stated that the SCC is more suitable for use in international discussions for now.

Response

The IWG agrees with those commenters who believe that use of the SCC estimates is an important component of regulatory impact analyses of rules that affect CO_2 emissions. However, it is not true that benefits that cannot be quantified or monetized are assigned zero weight in regulatory impact analysis. Although the monetized benefit estimates may not reflect unquantified benefits, the qualitative analysis provides important information about these benefits that must be given full consideration in regulatory decision-making. OMB guidance directs agencies to quantify benefits and costs of regulations to the extent feasible using the best available science and analytic techniques, but also to take non-quantified benefits into consideration when determining if the benefits of a regulatory action justify its costs. The SCC estimates and supporting TSDs are intended to assist agencies in adopting a consistent approach, based on the best available science and economics, for monetizing this important category of benefits. The IWG also agrees that the estimates should be updated periodically based on advances in the scientific and economic literature and has committed to do so.

Previous sections have addressed the perceived process flaws that have led some commenters to suggest that the estimates not be used until a future update that corrects these perceived flaws is completed. As noted, the IWG has accepted the suggestion of increased opportunity for public comment and plans to seek external expert advice as it considers futures updates, but does not feel that it is appropriate to withdraw the current estimates in the meantime as they represent the best available science in a form that is currently usable for monetized benefits estimates.

Regarding uncertainty, the IWG notes that most if not all benefits estimates in regulatory analyses are uncertain. This does not negate the value of the estimates. It does underscore the importance of a full and transparent discussion of uncertainty, and the TSDs have provided this (see, for example, *Section V: Limitations of the Analysis*, in the 2010 TSD, and *Section IV: Other Model Limitations and Research Gaps*, in the 2013 TSD). The TSDs are explicit that the estimates were developed for use in regulatory impact analysis. The 2010 TSD states that the SCC estimates were developed for use in "cost-benefit analyses of regulatory actions that have small, or 'marginal,' impacts on cumulative global emissions." The IWG has not addressed the use of the SCC estimates outside the regulatory context, such as in NEPA analysis,[14] state level decision making, and "pricing" carbon in the marketplace. In addition, the 2010 TSD states, "For policies that have a large (non-marginal) impact on global cumulative emissions, there is a separate question of whether the SCC is an appropriate tool for calculating the benefits of reduced emissions; we do not attempt to answer that question here." While the concept of an SCC is appropriate for international discussions, the IWG recognizes that any use of such estimates beyond the domestic regulatory context will require further discussion with our international partners; that said, our current work in this area can certainly help to inform such discussions.

11 Technical Addendum

As previously noted, the IWG continues to receive feedback from stakeholders through public comments on proposed Agency rulemakings that use the SCC in supporting analyses, the additional OMB comment period on the SCC, and regular interactions with stakeholders and research analysts implementing the methodology used by the IWG to compute the estimates. As a result of our engagement in this continuous review process, we recently discovered two areas where minor technical corrections are appropriate. First, the DICE model had been run up to 2300 rather than through 2300, as was intended, thereby leaving out the marginal damages in the last year of the time horizon. Second, due to an indexing error, the results from the PAGE model were in 2008 U.S. dollars rather than 2007 U.S. dollars, as was intended. A revised TSD with the corrected estimates (all models run through 2300 and all estimates in 2007 U.S. dollars) has been posted on OMB's website. On average the revised SCC estimates are one dollar less than the mean SCC estimates reported in the November 2013 TSD. The difference between the 95th percentile estimates with a 3% discount rate is slightly larger, as those estimates are heavily influenced by results from the PAGE model. The revised (July 2015) TSD includes an addition to the technical appendix (Appendix B) explaining these revisions.

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[14] On December, 18 2014, the Council on Environmental Quality released draft NEPA guidance on GHG Emissions and Climate Change Impacts (https://www.whitehouse.gov/administration/eop/ceq/initiatives/nepa/ghg-guidance). The draft guidance states: "When an agency determines it appropriate to monetize costs and benefits, then, although developed specifically for regulatory impact analyses, the Federal social cost of carbon, which multiple Federal agencies have developed and used to assess the costs and benefits of alternatives in rulemakings, offers a harmonized, interagency metric that can provide decision makers and the public with some context for meaningful NEPA review. When using the Federal social cost of carbon, the agency should disclose the fact that these estimates vary over time, are associated with different discount rates and risks, and are intended to be updated as scientific and economic understanding improves." The comment period for the draft guidance closed on March 25, 2015. CEQ is currently considering the comments received as it develops final guidance.

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