WildEarth
Guardians
A FORCE FOR NATURE

April 10, 2017

Via Hand Delivery

Ruth Welch
State Director
U.S. Bureau of Land Management
Colorado State Office
2850 Youngfield St.
Lakewood, CO 80215

Re: Protest of June 2017 Competitive Oil and Gas Lease Sale

Dear Ms. Welch:

Pursuant to 43 C.F.R. § 3120.1-3, WildEarth Guardians hereby protests the Bureau of Land Management's ("BLM's") proposal to offer 106 publicly owned oil and gas lease parcels covering 100.815.97 acres of land in the White River, Little Snake, and Kremmling Field Offies of Colorado for competitive sale on June 8, 2017. These parcels include public lands managed by BLM in Grand, Jackson, Routt, Moffat, and Rio Blanco Counties, Colorado. The specific parcels being protested include the following, as identified by the BLM's in its Final June 2017 Oil and Gas Sale List:[1]

Lease Parcel	Acres	County
COC78269	167.82	Routt
COC78270	722.20	Rio Blanco
COC78271	400.00	Rio Blanco
COC78272	600.06	Rio Blanco
COC78273	1,135.27	Rio Blanco
COC78274	1,583.82	Rio Blanco
COC78275	507.32	Rio Blanco
COC78276	924.26	Rio Blanco
COC78277	1,683.76	Rio Blanco
COC78278	192.59	Rio Blanco
COC78279	160.00	Rio Blanco
COC78280	40.00	Rio Blanco

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[1] This list, which was made available on March 10, 2017, is on the BLM's website at https://eplanning.blm.gov/epl-front-office/projects/nepa/70241/99316/120339/Sale_Notice_June2017.pdf.

COC78281	80.00	Rio Blanco
COC78282	711.14	Rio Blanco
COC78283	162.22	Rio Blanco
COC78284	1,362.71	Grand
COC78285	2,537.86	Grand
COC78286	1,873.80	Grand
COC78287	360.00	Grand
COC78288	1,626.66	Grand
COC78289	2,212.61	Grand
COC78290	2,390.41	Grand
COC78291	1,258.20	Grand
COC78292	1,239.13	Grand
COC78293	1,512.15	Grand
COC78294	232.87	Grand
COC78295	2,025.76	Grand
COC78296	1,580.23	Grand
COC78297	39.82	Jackson
COC78298	640.00	Jackson
COC78299	280.00	Jackson
COC78300	1,676.04	Grand
COC78301	1,186.20	Grand
COC78302	1,523.49	Grand
COC78303	1,678.48	Grand
COC78304	1,101.92	Grand
COC78305	719.80	Jackson
COC78306	719.68	Jackson
COC78307	1,544.11	Jackson
COC78308	1,160.00	Jackson
COC78309	1,400.00	Jackson
COC78310	158.80	Jackson
COC78311	1,347.50	Jackson
COC78312	825.09	Jackson
COC78313	320.00	Jackson
COC78314	110.13	Grand
COC78315	40.00	Grand
COC78316	1,007.43	Routt
COC78317	922.85	Routt
COC78318	715.05	Routt
COC78319	730.15	Routt
COC78320	1,200.00	Routt
COC78321	1,440.00	Routt

COC78322	1,990.86	Routt
COC78323	160.00	Routt
COC78324	920.00	Routt
COC78325	480.00	Routt
COC78326	120.00	Routt
COC78327	866.38	Routt
COC78328	240.00	Routt
COC78329	1,477.39	Routt
COC78330	680.00	Routt
COC78331	840.00	Routt
COC78332	125.16	Routt
COC78333	80.00	Routt
COC78334	562.47	Routt
COC78335	120.00	Routt
COC78336	80.00	Routt
COC78337	320.00	Routt
COC78338	1,080.00	Routt
COC78339	160.00	Routt
COC78340	639.54	Routt
COC78341	748.20	Moffat
COC78342	542.50	Moffat
COC78343	40.00	Rio Blanco
COC78344	557.75	Moffat
COC78345	1,240.91	Rio Blanco
COC78346	1,201.97	Rio Blanco
COC78347	1,740.50	Rio Blanco
COC78348	1,787.82	Rio Blanco
COC78349	1,808.82	Rio Blanco
COC78350	1,873.26	Rio Blanco
COC78351	1,917.52	Rio Blanco
COC78352	1,914.96	Rio Blanco
COC78353	1,834.59	Rio Blanco
COC78354	440.00	Rio Blanco
COC78355	640.00	Rio Blanco
COC78356	1,440.00	Rio Blanco
COC78357	2,230.00	Rio Blanco
COC78358	1,920.40	Rio Blanco
COC78359	2,164.84	Rio Blanco
COC78360	1,263.08	Rio Blanco
COC78361	799.92	Rio Blanco
COC78362	880.00	Rio Blanco

COC78363	870.79	Rio Blanco
COC78364	520.00	Rio Blanco
COC78365	880.00	Rio Blanco
COC78366	200.32	Rio Blanco
COC78367	1,400.84	Rio Blanco
COC78368	800.00	Rio Blanco
COC78369	1,274.56	Rio Blanco
COC78370	1,920.00	Rio Blanco
COC78371	460.16	Rio Blanco
COC78372	151.68	Rio Blanco
COC78373	356.03	Rio Blanco
COC78374	283.36	Rio Blanco

STATEMENT OF INTEREST

WildEarth Guardians is a nonprofit environmental advocacy organization dedicated to protecting the wildlife, wild places, wild rivers, and health of the American West. WildEarth Guardians is headquartered in Santa Fe, New Mexico, but has offices and staff throughout the western United States, including in Denver. On behalf of our members, Guardians has an interest in ensuring the BLM fully protects public lands and resources as it conveys the right for the oil and gas industry to develop publicly owned minerals. More specifically, Guardians has an interest in ensuring the BLM meaningfully and genuinely takes into account the climate implications of its oil and gas leasing decisions and objectively and robustly weighs the costs and benefits of authorizing the release of more greenhouse gas emissions that are known to contribute to global warming. WildEarth Guardians submitted comments on the BLM's proposed leasing on September 7, 2016 and December 12, 2016.

The mailing address for WildEarth Guardians to which correspondence regarding this protest should be directed is as follows:

WildEarth Guardians
2590 Walnut St.
Denver, CO 80205

STATEMENT OF REASONS

WildEarth Guardians protests the BLM's February 2017 oil and gas lease sale over the agency's failure to adequately analyze and assess the climate impacts of the reasonably foreseeable oil and gas development that will result in accordance with NEPA, 42 U.S.C. § 4331, *et seq*., and regulations promulgated thereunder by the White House Council on Environmental Quality ("CEQ"), 40 C.F.R. § 1500, *et seq*.

NEPA is our "basic national charter for protection of the environment." 40 C.F.R. § 1500.1(a). The law requires federal agencies to fully consider the environmental implications of their actions, taking into account "high quality" information, "accurate scientific analysis," "expert agency comments," and "public scrutiny," prior to making decisions. *Id.* at 1500.1(b). This consideration is meant to "foster excellent action," meaning decisions that are well informed and that "protect, restore, and enhance the environment." *Id.* at 1500.1(c).

To fulfill the goals of NEPA, federal agencies are required to analyze the "effects," or impacts, of their actions to the human environment prior to undertaking their actions. 40 C.F.R. § 1502.16(d). To this end, the agency must analyze the "direct," "indirect," and "cumulative" effects of its actions, and assess their significance. 40 C.F.R. §§ 1502.16(a), (b), and (d). Direct effects include all impacts that are "caused by the action and occur at the same time and place." 40 C.F.R. § 1508.8(a). Indirect effects are "caused by the action and are later in time or farther removed in distance, but are still reasonably foreseeable." *Id.* at § 1508.8(b). Cumulative effects include the impacts of all past, present, and reasonably foreseeable actions, regardless of what entity or entities undertake the actions. 40 C.F.R. § 1508.7.

An agency may prepare an environmental assessment ("EA") to analyze the effects of its actions and assess the significance of impacts. *See* 40 C.F.R. § 1508.9; *see also* 43 C.F.R. § 46.300. Where effects are significant, an Environmental Impact Statement ("EIS") must be prepared. *See* 40 C.F.R. § 1502.3. Where significant impacts are not significant, an agency may issue a Finding of No Significant Impact ("FONSI") and implement its action. *See* 40 C.F.R. § 1508.13; *see also* 43 C.F.R. § 46.325(2).

Within an EA or EIS, the scope of the analysis must include "[c]umulative actions" and "[s]imilar actions." 40 C.F.R. §§ 1508.25(a)(2) and (3). Cumulative actions include action that, "when viewed with other proposed actions have cumulatively significant impacts and should therefore be discussed in the same impact statement." 40 C.F.R. § 1508.25(a)(2). Similar actions include actions that, "when viewed with other reasonably foreseeable or proposed agency actions, have similarities that provide a basis for evaluating their environmental consequences together." 40 C.F.R. § 1508.25(a)(3). Key indicators of similarities between actions include "common timing or geography." *Id.*

Here, the BLM fell short of complying with NEPA with regards to analyzing and assessing the potentially significant impacts of oil and gas leasing. In support of its proposed leasing, the agency prepared an EA that failed to analyze the reasonably foreseeable greenhouse gas emissions and climate impacts that would result from selling the oil and gas lease parcels, as well as failed to address potentially significant impacts to sage grouse and other wildlife. The agency's proposed FONSI is therefore unsupported and any decision to sell and issue the aforementioned lease parcels cannot be sustained. Either the BLM must prepare an EIS or it cannot proceed with the lease sale as proposed. Below, we detail how BLM's proposal fails to comply with NEPA.

1. The BLM Failed to Analyze and Assess the Direct, Indirect, and Cumulative Impacts of Greenhouse Gas Emissions that Would Result from Issuing the Proposed Lease Parcels

In the EA, the BLM completely rejected analyzing and assessing the potential direct and indirect greenhouse gas emissions, including carbon dioxide and methane, that would result from the reasonably foreseeable development of the proposed leases. Although acknowledging that development of the lease parcels would occur and that greenhouse gas emissions would be produced, no analysis of these emissions was actually prepared.

The BLM appears to assert that estimates of emissions are impossible to determine because it is impossible to determine what reasonably foreseeable development may occur. However, as the agency notes in at least the EA, reasonably foreseeable development scenarios have been analyzed. *See* EA at 49. In this case, although BLM may not know precisely how many wells will be developed, the agency knows that some wells will clearly be developed, and that over the life of the current Resource Management Plans, a certain number of wells are likely to be developed. This cannot support a conclusion that zero wells will be developed, which the BLM appears to advance.

The BLM's position is all the more egregious given that other BLM Field Offices, including, but not limited to, the Vernal Field Office in Utah, Four Rivers Field Office in Idaho, the Billings Field Office in Montana, the Royal Gorge Field Office in Colorado, and others have not only estimated reasonably foreseeable greenhouse gas emissions associated with the development of oil and gas leases, but clearly do not believe that such information is not "impossible" to analyze under NEPA.

Most recently, in the Vernal Field Office of Utah, the BLM developed an estimate of both direct and indirect emissions related to proposed oil and gas leasing. In an EA prepared in October, the agency explained:

> Direct greenhouse gas emissions from speculative future oil and gas well production on the proposed lease parcels was calculated assuming one well per parcel. Total Greenhouse Gas Warming Potential (GWP), which includes direct emissions of carbon dioxide, methane, and nitrous oxide from an oil or gas producing well is estimated based on the emissions estimates from the Greater Monument Buttes Final Environmental Impact Statement ([BLM 2016] Table 4.2.1.1.1-1), which is the most recent NEPA calculation of GHG in the lease area. The per-well GWP emissions estimate was made by dividing the Project Total GWP emissions in Table 4.2.1.1.1-1 (3,096,936 tpy) by the total number of producing oil and gas wells used to generate the GWP emissions estimates (5,740 wells). This gives a GWP emissions estimate of approximately 540 tons per year GWP emissions on a per-well, per-parcel basis. Actual emissions may range from zero if a parcel is not leased or not developed after leasing, to an unknown upper range.

Exhibit 2 to Guardians' December 12, 2016 Comments at 39-40, available online at https://eplanning.blm.gov/epl-front-office/projects/nepa/59590/86059/103236/Fianl_for_Posting.pdf. In this EA, the BLM not only analyzed and assessed direct greenhouse gas emissions, but also estimated reasonably foreseeable indirect emissions related to the consumption of oil and gas produced from proposed leases. In its EA, the BLM presented an estimate of "low," "average," and "high" emissions, reporting that consumption related emissions could be nearly 500,000 metric tons of carbon dioxide equivalent annually. *See id.* at 40.

In the Four Rivers Field Office of Idaho, the BLM utilized an emission calculator developed by air quality specialists at the BLM National Operations Center in Denver to estimate likely greenhouse gases that would result from leasing five parcels. *See* Exhibit 9 to Guardians' September 7, 2016 Scoping Comments at 41. The agency estimated that 2,893.7 tons of carbon dioxide equivalent ("CO_2e") would be released per well. *Id.* at 35. Based on the analyzed alternatives, which projected between 5 and 25 new wells, the BLM estimated that total greenhouse gas emissions would be between 14,468.5 tons and 72,342.5 tons annually. *Id.*

Although the BLM may assert that such information is not possible to analyze, there is no basis for such a claim. Not only has the agency estimated reasonably foreseeable development and disclosed in the EAs that greenhouse gas emissions are a likely reasonably foreseeable consequence of issuing the leases, but using the agency's own logic, this would mean that any analysis of future environmental impacts would be incredibly uncertain. Of course, this would completely undermine NEPA's mandate that significance be based on "uncertain[ty]." 40 C.F.R. § 1508.27(b)(5). Indeed, if the climate impacts of oil and gas leasing are, as the BLM asserts, so uncertain, then an EIS is justified. As CEQ states, whether or not impacts are significant, and therefore trigger the need to prepare an EIS, are based on whether impacts are "highly uncertain or involve unique or unknown risks." *Id.* The BLM cannot summarily dismiss significant issues, such as climate change, on the basis of uncertainty without assessing whether this uncertainty necessitates preparation of an EIS.

Regardless, the agency's arguments in the EAs are belied by the fact that, as just discussed, other BLM Field Offices clearly believe that an analysis of reasonably foreseeable greenhouse gas emissions is not only reasonable, but also possible and useful.

Adding to the shortcomings in the EAs is that the BLM failed to analyze the cumulative impacts of greenhouse gas emissions from past, present, and reasonably foreseeable oil and gas development. As noted above, other BLM Field Offices have analyzed the likely greenhouse gas emissions that would result based on the BLM's own reasonably foreseeable development scenarios. In this case, the BLM has not made any attempt to estimate greenhouse gas emissions that would result from oil and gas development likely to occur under the agency's reasonably foreseeable development scenarios, both for the Field Offices at issue here and for Field Offices undertaking oil and gas leasing elsewhere in Colorado and the American West.

In the EA, the BLM appears to insinuate that greenhouse gas emissions from reasonably foreseeable oil and gas development would simply be insignificant. This assertion, however, defies the required scope of the BLM's analysis. Under NEPA, an agency must analyze the impacts of "similar" and "cumulative" actions in the same NEPA document in order to adequately disclose impacts in an EIS or provide sufficient justification for a FONSI in an EA. *See* 40 C.F.R. §§ 1508.25(a)(2) and (3). Here, the BLM was required to at least take into account the greenhouse gas emissions resulting from other proposed oil and gas leasing in Colorado, if not beyond, as well as related oil and gas development, and to analyze the impacts of these actions in terms of their direct, indirect, and cumulative impacts.

The failure to address cumulative greenhouse gas emissions is made worse by the fact that the underlying Final EISs prepared for the White River, Little Snake, and Kremmling Field Offices' Resource Management Plans nowhere analyze or assess greenhouse gas emissions associated with oil and gas development. In light of this, the BLM clearly has no basis to conclude that greenhouse gas emissions resulting from the reasonably foreseeable impacts of oil and gas development associated with the proposed leasing would not be significant. Without any analysis of cumulative greenhouse emissions whatsoever, the agency's proposed FONSIs are unsupported under NEPA.

The BLM finally attempts to argue that an analysis of greenhouse gas emissions is more appropriate at the drilling stage. We have yet to see the BLM actually prepare such a site-specific analysis in conjunction with an oil and gas lease development proposal. What's more, this argument has no merit as the agency has proposed no stipulations that would grant the BLM discretion to limit, or outright prevent, development of the proposed leases on the basis of greenhouse gas emissions and/or climate concerns. The BLM is effectively proposing to make an irreversible commitment of resources, which is the hallmark of significance under NEPA. *See* 42 U.S.C. § 4332(c)(v) and 40 C.F.R. § 1502.16. The failure to prepare an EIS—or any analysis for that matter—for the proposed leases is therefore contrary to NEPA.

2. The BLM Failed to Analyze the Costs of Reasonably Foreseeable Carbon Emissions Using Well-Accepted, Valid, Credible, GAO-Endorsed, Interagency Methods for Assessing Carbon Costs that are Supported by the White House

Compounding the failure of the BLM to make any effort to estimate the greenhouse gas emissions that would result from reasonably foreseeable oil and gas development is that the agency also rejected analyzing and assessing these emissions in the context of their costs to society. It is particularly disconcerting that the agency refused to analyze and assess costs using the social cost of carbon protocol, a valid, well-accepted, credible, and interagency endorsed method of calculating the costs of greenhouse gas emissions and understanding the potential significance of such emissions.

The social cost of carbon protocol for assessing climate impacts is a method for "estimat[ing] the economic damages associated with a small increase in carbon dioxide (CO2) emissions, conventionally one metric ton, in a given year [and] represents the value of damages avoided for a small emission reduction (i.e. the benefit of a CO2 reduction)." Exhibit 1 to Guardians' September 7, 2016 Comments. The protocol was developed by a working group consisting of several federal agencies, including the U.S. Department of Agriculture, EPA, CEQ, and others, with the primary aim of implementing Executive Order 12866, which requires that the costs of proposed regulations be taken into account.

In 2009, an Interagency Working Group was formed to develop the protocol and issued final estimates of carbon costs in 2010. These estimates were then revised in 2013 by the Interagency Working Group, which at the time consisted of 13 agencies, including the

Department of Agriculture. This report and the social cost of carbon estimates were again revised in 2015. *See* Exhibit 4 to Guardians' September 8, 2016 Comments. Again, this report and social cost of carbon estimates were revised in 2016. *See* Exhibit 1 to this Protest, Interagency Working Group on Social Cost of Carbon, "Technical Support Document: Technical Update of the Social Cost of Greenhouse Gases for Regulatory Impact Analysis Under Executive Order 12866" (Aug. 2016).

Most recently, as an addendum to previous Technical Support Documents regarding the social cost of carbon, the Department of the Interior joined numerous other agencies in preparing estimates of the social cost of methane and other greenhouse gases. *See* Exhibit 2 to this Protest, Interagency Working Group on Social Cost of Greenhouse Gases, United States Government, "Addendum to Technical Support Document on Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866: Application of the Methodology to Estimate the Social Cost of Methane and the Social Cost of Nitrous Oxide" (Aug. 2016).

Depending on the discount rate and the year during which the carbon emissions are produced, the Interagency Working Group estimates the cost of carbon emissions, and therefore the benefits of reducing carbon emissions, to range from $10 to $212 per metric ton of carbon dioxide. *See* Chart Below. In its most recent update to the Social Cost of Carbon Technical Support Document, the White House's central estimate was reported to be $36 per metric ton. *See* Exhibit 5 to Guardians' September 7, 2016 Comments, White House, "Estimating the Benefits from Carbon Dioxide Emissions Reductions." In July 2014, the U.S. Government Accountability Office ("GAO") confirmed that the Interagency Working Group's estimates were based on sound procedures and methodology. *See* Exhibit 6 to Guardians' September 7, 2016 Comments, GAO, "Regulatory Impact Analysis, Development of Social Cost of Carbon Estimates," GAO-14-663 (July 2014), available online at http://www.gao.gov/assets/670/665016.pdf.

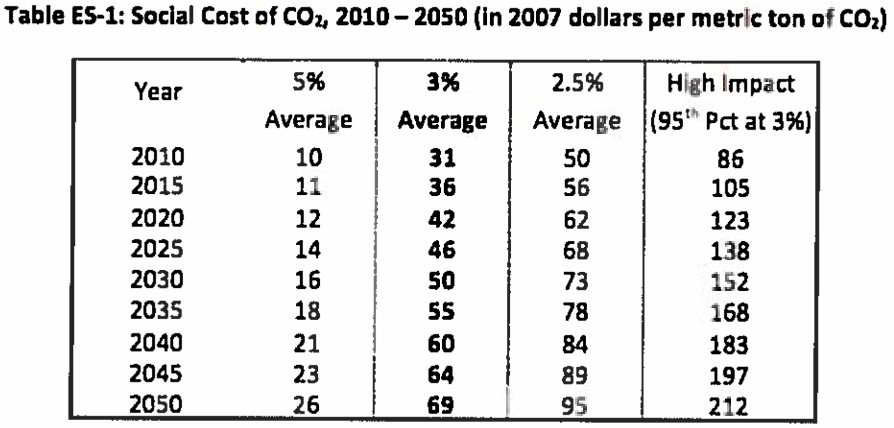

Table ES-1: Social Cost of CO_2, 2010 – 2050 (in 2007 dollars per metric ton of CO_2)

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

Most recent social cost of carbon estimates presented by Interagency Working Group on Social Cost of Carbon. The 95th percentile value is meant to represent "higher-than-expected" impacts from climate change.

Although often utilized in the context of agency rulemakings, the protocol has been recommended for use and has been used in project-level decisions. For instance, the EPA recommended that an EIS prepared by the U.S. Department of State for the proposed Keystone XL oil pipeline include "an estimate of the 'social cost of carbon' associated with potential increases of GHG emissions." Exhibit 7 to Guardians' September 7, 2016 Comments.

More importantly, the BLM has also utilized the social cost of carbon protocol in the context of oil and gas leasing. In recent Environmental Assessments for oil and gas leasing in Montana, the agency estimated "the annual SCC [social cost of carbon] associated with potential development on lease sale parcels." Exhibit 8 to Guardians' September 7, 2016 Comments at 71. In conducting its analysis, the BLM used a "3 percent average discount rate and year 2020 values," presuming social costs of carbon to be $46 per metric ton. *Id.* In Idaho, the BLM also utilized the social cost of carbon protocol to analyze and assess the costs of oil and gas leasing. Using a 3% average discount rate and year 2020 values, the agency estimated the cost of carbon to be $51 per ton of annual CO_2e increase. *See* Exhibit 9 to Guardians' September 7, 2016 Comments at 81. Based on this estimate, the agency estimated that the total carbon cost of developing 25 wells on five lease parcels to be $3,689,442 annually. *Id.* at 83.

To be certain, the social cost of carbon protocol presents a conservative estimate of economic damages associated with the environmental impacts climate change. As the EPA has noted, the protocol "does not currently include all important [climate change] damages." Exhibit 1 to Guardians' September 7, 2016 Comments. As explained:

> The models used to develop [social cost of carbon] estimates do not currently include all of the important physical, ecological, and economic impacts of climate change recognized in the climate change literature because of a lack of precise information on the nature of damages and because the science incorporated into these models naturally lags behind the most recent research.

Id. In fact, more recent studies have reported significantly higher carbon costs. For instance, a report published this month found that current estimates for the social cost of carbon should be increased six times for a mid-range value of $220 per ton. *See* Exhibit 10 to Guardians' September 7, 2016 Comments at 2. In spite of uncertainty and likely underestimation of carbon costs, nevertheless, "the SCC is a useful measure to assess the benefits of CO2 reductions," and thus a useful measure to assess the costs of CO2 increases. Exhibit 1 to Guardians' September 7, 2016 Comments.

That the economic impacts of climate change, as reflected by an assessment of social cost of carbon, should be a significant consideration in agency decisionmaking, is emphasized by a recent White House report, which warned that delaying carbon reductions would yield significant economic costs. *See* Exhibit 11 to Guardians' September 7, 2016 Comments, Executive Office of the President of the United States, "The Cost of Delaying Action to Stem Climate Change" (July 2014), available online at https://www.whitehouse.gov/sites/default/files/docs/the_cost_of_delaying_action_to_stem_climate_change.pdf. As the report states:

> [D]elaying action to limit the effects of climate change is costly. Because CO_2 accumulates in the atmosphere, delaying action increases CO_2 concentrations. Thus, if a policy delay leads to higher ultimate CO_2 concentrations, that delay produces persistent economic damages that arise from higher temperatures and higher CO_2 concentrations. Alternatively, if a delayed policy still aims to hit a given climate target, such as limiting CO_2 concentration to given level, then that delay means that the policy, when implemented, must be more stringent and thus more costly in subsequent years. In either case, delay is costly.

Exhibit 11 to Guardians' September 7, 2016 Comments at 1.

The requirement to analyze the social cost of carbon is supported by the general requirements of NEPA and federal case law. As explained, NEPA requires agencies to analyze the consequences of proposed agency actions and consider include direct, indirect, and cumulative consequences. In terms of oil and gas leasing, an analysis of site-specific impacts must take place at the lease stage and cannot be deferred until after receiving applications to drill. *See New Mexico ex rel. Richardson v. Bureau of Land Management*, 565 F.3d 683, 717-18 (10th Cir. 2009); *Conner v. Burford,* 848 F.2d 1441 (9th Cir.1988); *Bob Marshall Alliance v. Hodel,* 852 F.2d 1223, 1227
(9th Cir.1988).

To this end, courts have ordered agencies to assess the social cost of carbon pollution, even before a federal protocol for such analysis was adopted. In 2008, the U.S. Court of Appeals for the Ninth Circuit ordered the National Highway Traffic Safety Administration to include a monetized benefit for carbon emissions reductions in an Environmental Assessment prepared under NEPA. *Center for Biological Diversity v. National Highway Traffic Safety Administration*, 538 F.3d 1172, 1203 (9th Cir. 2008). The Highway Traffic Safety Administration had proposed a rule setting corporate average fuel economy standards for light trucks. A number of states and public interest groups challenged the rule for, among other things, failing to monetize the benefits that would accrue from a decision that led to lower carbon dioxide emissions. The Administration had monetized the employment and sales impacts of the proposed action. *Id.* at 1199. The agency argued, however, that valuing the costs of carbon emissions was too uncertain. *Id.* at 1200. The court found this argument to be arbitrary and capricious. *Id.* The court noted that while estimates of the value of carbon emissions reductions occupied a wide range of values, the correct value was certainly not zero. *Id.* It further noted that other benefits, while also uncertain, were monetized by the agency. *Id.* at 1202.

More recently, a federal court has done likewise for a federally approved coal lease. That court began its analysis by recognizing that a monetary cost-benefit analysis is not universally required by NEPA. *See High Country Conservation Advocates v. U.S. Forest Service*, 52 F.Supp.3d 1174 (D. Colo. 2014), citing 40 C.F.R. § 1502.23. However, when an agency prepares a cost-benefit analysis, "it cannot be misleading." *Id.* at 1182 (citations omitted). In that case, the NEPA analysis included a quantification of benefits of the project. However, the quantification of the social cost of carbon, although included in earlier analyses, was omitted in the final NEPA analysis. *Id.* at 1196. The agencies then relied on the stated benefits of the project to justify project approval. This, the court explained, was arbitrary and capricious. *Id.* Such approval was based on a NEPA analysis with misleading economic assumptions, an approach long disallowed by courts throughout the country. *Id.*

A recent op-ed in the New York Times from Michael Greenstone, the former chief economist for the President's Council of Economic Advisers, confirms that it is appropriate and acceptable to calculate the social cost of carbon when reviewing whether to approve fossil fuel extraction. *See* Exhibit 12 to Guardians' September 7, 2016 Comments, Greenstone, M., "There's a Formula for Deciding When to Extract Fossil Fuels," *New York Times* (Dec. 1, 2015), available online at http://www.nytimes.com/2015/12/02/upshot/theres-a-formula-for-deciding-when-to-extract-fossil-fuels.html?_r=0.

In light of all this, it appears more than reasonable to have expected the BLM to take into account carbon costs as part of its NEPA analyses. The agency did not. In fact, the BLM did not even address carbon costs in its EA.

The fact that the BLM has, in the context of other oil and gas lease sale environmental analyses, clearly acknowledged that social cost of carbon analyses are appropriate, useful, and possible, the refusal of the agency to similarly undertake such analyses in the current context is unsupported under NEPA and cannot stand to support the decision to offer the aforementioned lease parcels for sale and issuance in June 2017.

Sincerely,

Jeremy Nichols
Climate and Energy Program Director
WildEarth Guardians
2590 Walnut St.
Denver, CO 80205
(303) 437-7663
jnichols@wildearthguardians.org

Exhibit 1

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 95th 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

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[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.

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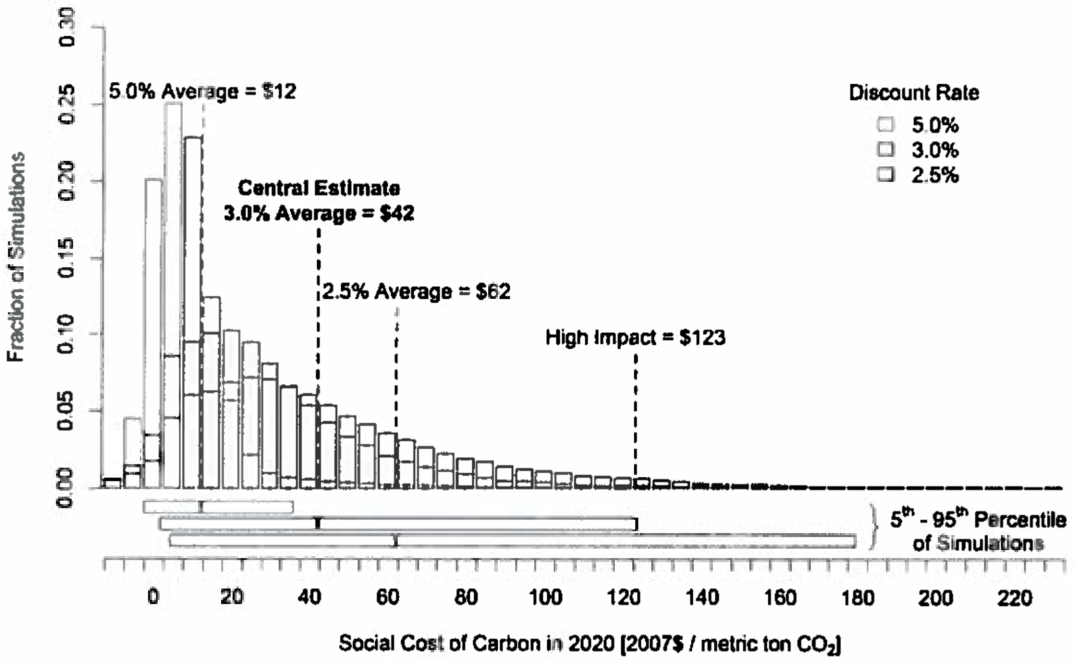
[2] See e.g. OMB Circular A-4, section on *Treatment of Uncertainty*. Available at: https://www.whitehouse.gov/omb/circulars_a004_a-4/#e.

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



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[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

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[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

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[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.

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 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]

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[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).

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.

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[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.

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

Table 3: Average Annual Growth Rates of SC-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-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-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-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-CO_2]" in a recent article on the SC-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.

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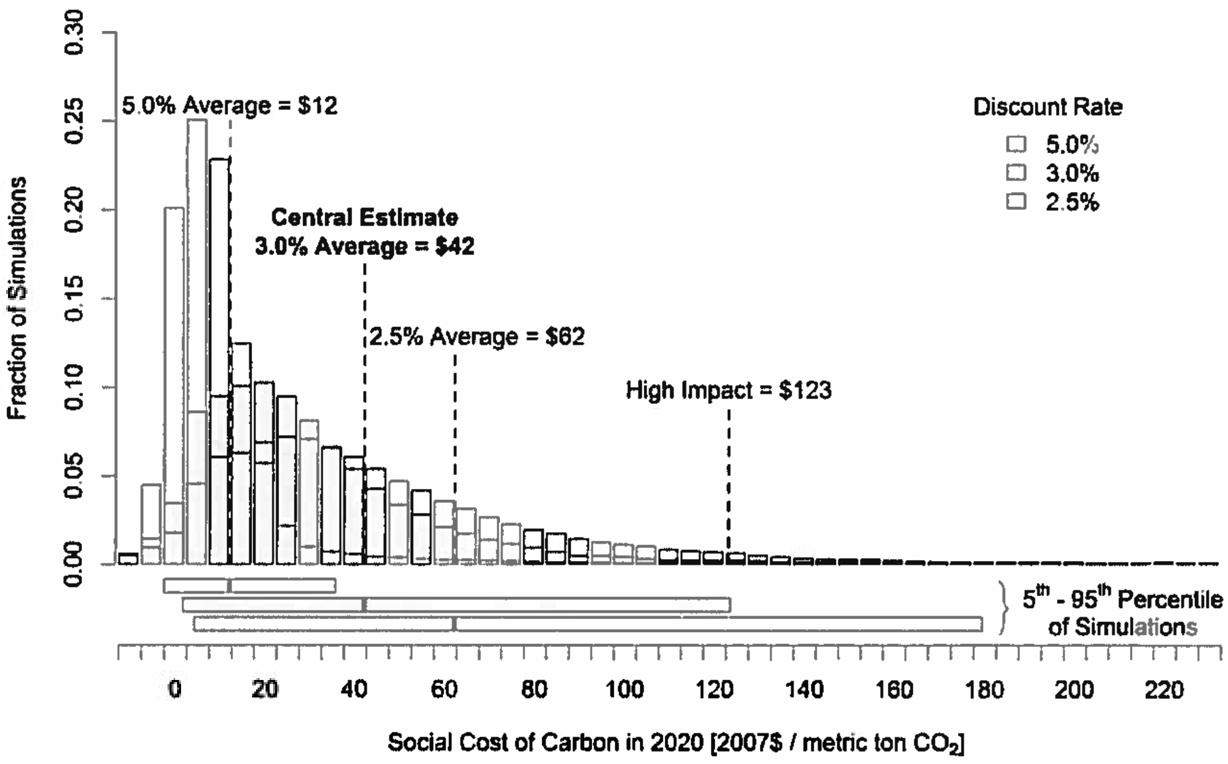
[16] Although the distributions in Figure 1 are based on the full set of model results (150,000 estimates for each discount rate), for display purposes the horizontal axis is truncated with 0.1 to 0.6 percent of the estimates lying below the lowest bin displayed and 0.2 to 3.7 percent of the estimates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

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[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

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[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

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

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.

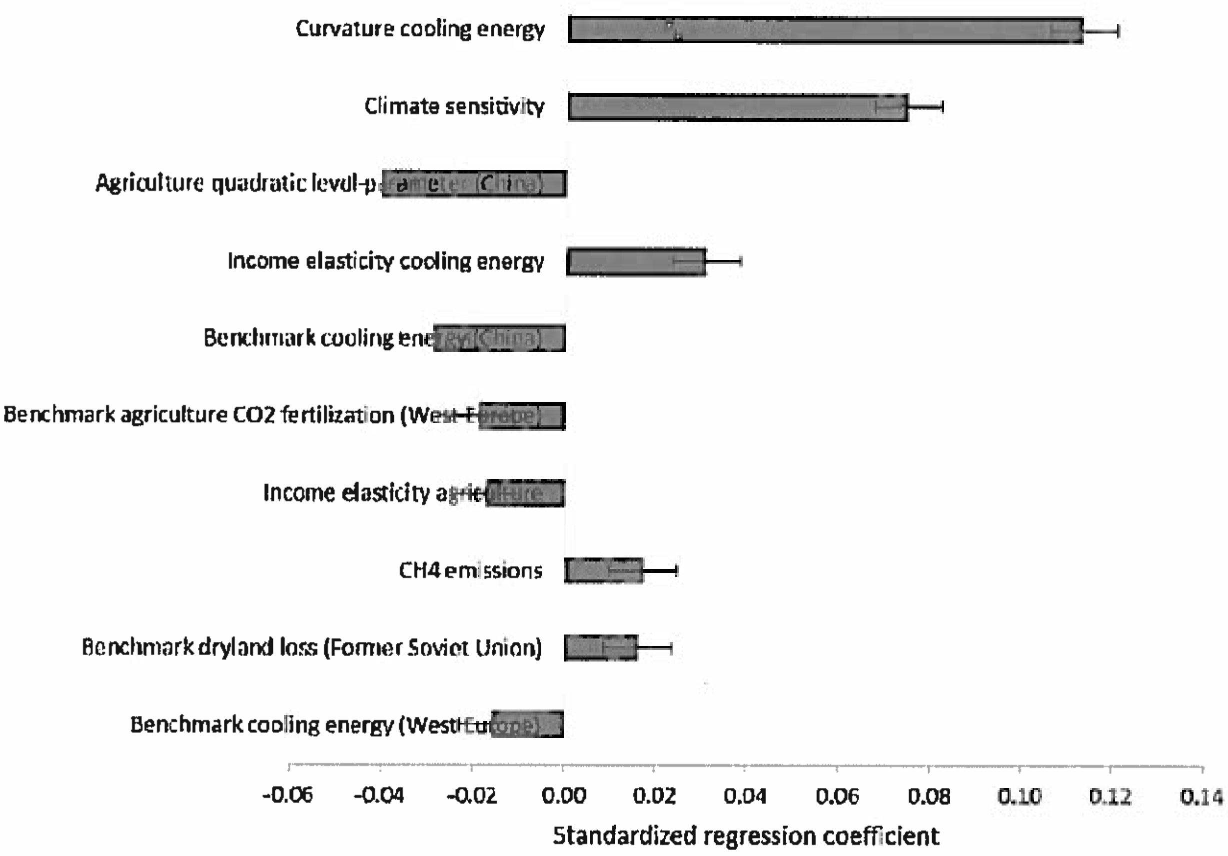

Figure C1: Influence of Key Uncertain Parameters in Default FUND Model (Anthoff and Tol 2013a)[19]

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

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[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.

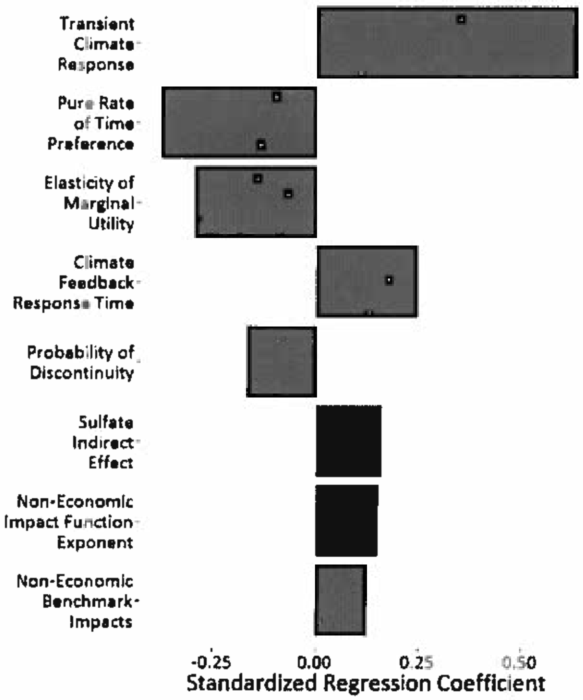

Figure C2: Influence of Key Uncertain Parameters in Default PAGE Model (Hope 2013)[21]

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[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.

Exhibit 2

Addendum to Technical Support Document on Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866: Application of the Methodology to Estimate the Social Cost of Methane and the Social Cost of Nitrous Oxide

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

Addendum:

Valuing Methane and Nitrous Oxide Emission Changes in Regulatory Benefit-Cost Analysis

I. Introduction

While carbon dioxide (CO_2) is the most prevalent greenhouse gas (GHG) emitted into the atmosphere, other GHGs are also important contributors: methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride.[1] The potential of these gases to change the Earth's climate relative to CO_2 is commonly represented by their 100-year global warming potential (GWP). GWPs measure the contribution to warming of the Earth's atmosphere resulting from emissions of a given gas (i.e., radiative forcing per unit of mass) over a particular timeframe relative to CO_2. As such, GWPs are often used to convert emissions of non-CO_2 GHGs to CO_2-equivalents to facilitate comparison of policies and inventories involving different GHGs.

While GWPs allow for some useful comparisons across gases on a physical basis, using the social cost of carbon dioxide (SC-CO_2)[2] to value the damages associated with changes in CO_2-equivalent emissions is not optimal. This is because non-CO_2 GHGs differ not just in their potential to absorb infrared radiation over a given time frame, but also in the temporal pathway of their impact on radiative forcing, which is relevant for estimating their social cost but not reflected in the GWP. Physical impacts other than temperature change also vary across gases in ways that are not captured by GWP. For instance, CO_2 emissions, unlike CH_4 and other GHGs, contribute to ocean acidification. Likewise, damages from CH_4 emissions are not offset by any positive effect of CO_2 fertilization on agriculture. Thus, transforming gases into CO_2-equivalents using GWP, and then multiplying the CO_2-equivalents by the SC-CO_2, is not as accurate as a direct calculation of the social costs of non-CO_2 GHGs.[3]

In light of these limitations and the paucity of peer-reviewed estimates of the social cost of non-CO_2 gases in the literature, the 2010 SC-CO_2 Technical Support Document (TSD)[4] did not include an estimate of the social cost of non-CO_2 GHGs and did not endorse the use of GWP to approximate the value of non-CO_2 emission changes in regulatory analysis. Instead, the Interagency Working Group (IWG) noted that more work was needed to link non-CO_2 GHG emission changes to economic impacts.

Since that time, new estimates of the social cost of non-CO_2 GHG emissions have been developed in the scientific literature, and a recent study by Marten et al. (2015) provided the first set of published estimates

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[1] See EPA Endangerment Finding: Endangerment and Cause or Contribute Findings for Greenhouse Gases under Section 202(a) of the Clean Air Act, 74 Fed. Reg. 66,496 (Dec. 15, 2009).

[2] Throughout this Addendum we refer to the estimates as "SC-CO_2 estimates" rather than the more simplified "SCC" abbreviation that was previously used by the IWG.

[3] For more detailed discussion of the limitations of using a GWP based approach to valuing non-CO_2 GHG emission changes, see, e.g., Marten et al. (2015) and recent EPA regulatory impact analyses (e.g., EPA 2016a).

[4] The 2010 SC-CO_2 TSD and subsequent updates are available at: https://www.whitehouse.gov/omb/oira/social-cost-of-carbon.

for the social cost of CH_4 and N_2O emissions that are consistent with the methodology and modeling assumptions underlying the IWG SC-CO_2 estimates. Specifically, Marten et al. used the same set of three integrated assessment models (IAMs), five socioeconomic and emissions scenarios, equilibrium climate sensitivity distribution, three constant discount rates, and the aggregation approach used by the IWG to develop the SC-CO_2 estimates. This addendum summarizes the Marten et al. methodology and presents the SC-CH_4 and SC-N_2O estimates from that study as a way for agencies to incorporate the social benefits of reducing CH_4 and N_2O emissions into benefit-cost analyses of regulatory actions that have small, or "marginal," impacts on cumulative global emissions. As stated in the 2010 TSD, most federal regulatory actions can be expected to have impacts on global emissions that may be considered marginal in this context. In the future, this addendum may include values for the social cost of additional non-CO_2 greenhouse gases.

The SC-CH_4 and SC-N_2O estimates presented in this addendum offer a method for improving the analyses of regulatory actions that are projected to influence CH_4 or N_2O emissions in a manner consistent with how CO_2 emission changes are valued. The estimates are presented with an acknowledgement of the limitations and 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, just as the IWG has committed to do for SC-CO_2.

The methodology and estimates described in this addendum have undergone multiple stages of peer review and their use in regulatory analysis has been subject to public comment. With regard to peer review, the study by Marten et al. (2015) was subjected to a standard double-blind peer review process prior to journal publication. In addition, the application of these estimates to federal regulatory analysis was designated as Influential Scientific Information (ISI), and its external peer review was added to the EPA Peer Review Agenda for Fiscal Year 2015 in November 2014. The public was invited to provide comment on the peer review plan, though EPA did not receive any comments. The external peer reviewers agreed with EPA's interpretation of Marten et al.'s estimates; generally found the estimates to be consistent with the approach taken in the IWG SC-CO_2 estimates; and concurred with the limitations of the GWP approach, finding directly modeled estimates to be more appropriate. All documents pertaining to the external peer review, including a white paper summarizing the methodology, the charge questions, and each reviewer's full response is available on the EPA Science Inventory website.[5] For a discussion of public comments on the valuation of non-CO_2 GHG impacts in general and the use of the Marten et al. estimates for the SC-CH_4, see recent EPA regulations with CH_4 impacts (e.g., EPA 2012a, 2012b, 2016a, 2016b) and for the SC-N_2O, see recent EPA and DOT regulations with N_2O impacts (e.g., EPA and DOT 2016). OMB has determined that the use of the Marten et al. estimates in regulatory analysis is consistent with the requirements of OMB's Information Quality Guidelines Bulletin for Peer Review and OMB Circular A-4.

II. Overview of Methodology

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[5] The complete record for this review is available on the EPA Science Inventory website at: http://cfpub.epa.gov/si/si_public_pra_view.cfm?dirEntryID=291976.

The social cost of non-CO_2 GHG emissions can be directly estimated using an IAM similar to the way in which the SC-CO_2 is estimated. As discussed at length in the 2010 SC-CO_2 TSD, IAMs couple simplified models of atmospheric gas cycles and climate systems with highly aggregated models of the global economy and human behavior to represent the impacts of GHG emissions on the climate and human welfare. Within IAMs, the equations that represent the influence of emissions on the climate are based on scientific assessments, while the equations that map climate impacts to human welfare are based on economic research that has studied the effects of climate on various market and non-market sectors. Estimating the social cost of emissions for a given GHG at the margin involves perturbing the emissions of that gas in a given year and forecasting the increase in monetized climate damages relative to the baseline. These incremental damages are then discounted back to the perturbation year to represent the marginal social cost of emissions of the specific GHG in that year.

Several researchers have directly estimated the social cost of non-CO_2 GHG emissions using IAMs. Among these published estimates there is considerable variation in the models and input assumptions. Fankhauser (1994) developed a simple IAM to estimate the average SC-CH_4 and SC-N_2O for emissions in the 2010 and 2020 decades given a 100-year time horizon for climate change damages. Kandlikar (1995) and Hammitt et al. (1996) also developed simple models to estimate the social cost of CH_4, N_2O, and other gases for a single socio-economic-emissions scenario and using constant discount rates. Tol et al. (2003) and Hope (2005, 2006) developed estimates for the SC-CH_4 in 2000 using the FUND and PAGE models, respectively. Waldhoff et al. (2011) used a newer version of the FUND model to develop estimates of the social cost of marginal CH_4, N_2O, and sulfur hexafluoride (SF_6) emissions for the average year in the 2010-2019 decade. While they considered only a single emissions period, they conducted a wide range of sensitivity analyses including four socio-economic-emissions scenarios, in addition to the default FUND scenario.

These studies differ in the emission perturbation year, employ a wide range of constant and variable discount rate specifications, and consider a range of baseline socioeconomic and emissions scenarios that have been developed over the last 20 years. However, none of these published estimates of the SC-CH_4 and SC-N_2O are consistent with the modeling assumptions underlying the IWG SC-CO_2 estimates, and most are likely underestimates due to changes in the underlying science since their publication. Therefore, Marten et al. (2015) provide the first set of direct estimates of the SC-CH_4 and SC-N_2O that are consistent with the SC-CO_2 estimates currently used in federal regulatory analysis.

The estimation approach of Marten et al. (2015) used the same set of three IAMs, five socio-economic-emissions scenarios, equilibrium climate sensitivity distribution, and three constant discount rates used to develop the IWG SC-CO_2 estimates. Details on each of these inputs are provided in the 2010 SC-CO_2 TSD. Marten et al. also used the same aggregation method as the IWG to distill the 45 distributions of the SC-CH_4 and SC-N_2O produced for each emissions year into four estimates for use in regulatory analysis. Three values are based on the average SC-CH_4 and the average SC-N_2O from the three IAMs, at discount rates of 2.5, 3, and 5 percent. As discussed in the 2010 TSD, there is extensive evidence in the scientific and economic literature of 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 included to represent the marginal damages associated with these lower-probability, higher-impact outcomes. Accordingly, this value is selected from further out in the tail of the distributions of SC-CH_4 and SC-N_2O estimates; specifically, the fourth value corresponds to the 95th percentile of the frequency distributions of SC-CH_4 and SC-N_2O estimates based on a 3 percent discount rate.

The IWG has determined that it is reasonable to use the same focus on global benefits for valuing emission reductions that was used to estimate the SC-CO_2. This is because anthropogenic climate change involves a global externality: emissions of most greenhouse gases (including CH_4 and N_2O) 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, estimates of the social cost of CH_4 and N_2O must incorporate the full (global) damages caused by emissions. In addition, climate change presents a problem that the United States alone cannot solve. Other countries will also need to take action to reduce GHG emissions if significant changes in the global climate are to be avoided. Furthermore, 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. Thus, consistent with the approach for the SC-CO_2, the IWG concluded that a global measure of the benefits from reducing U.S. CH_4 and N_2O emissions is preferable. Similarly, the IWG has determined that the range of discount rates used to estimate SC-CO_2 are appropriate for estimating SC-CH_4 and SC-N_2O as well. The rationale put forth in the 2010 TSD to use this set of discount rates because of the intergenerational nature of CO_2 impacts also applies to CH_4 and N_2O. Although the atmospheric lifetime of CH_4 is notably shorter than that of CO_2, the impacts of changes in contemporary CH_4 emissions are also expected to occur over long time horizons that cover multiple generations, and the lifetime of N_2O is almost 10 times as long as the lifetime of CH_4.[6] For additional discussion see the SC-CO_2 TSD.[7]

In order to develop SC-CH_4 and SC-N_2O estimates consistent with the methodology underlying the SC-CO_2 estimates, Marten et al. (2015) needed to augment the IWG modeling framework in two respects: 1) augment the climate model of two of the IAMs to explicitly consider the path of additional radiative forcing from a CH_4 or N_2O perturbation, and 2) add more specificity to the assumptions regarding post-2100 baseline CH_4 and N_2O emissions.

Regarding the climate modeling, both the DICE and PAGE models as implemented by the IWG to estimate SC-CO_2 use an exogenous projection of aggregate non-CO_2 radiative forcing, which prevents one from introducing a direct perturbation of CH_4 or N_2O emissions into the models and then observing its effects.[8]

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[6] The IPCC Fifth Assessment Report (AR5) estimates a central tendency for the e-folding time of CH_4 in the atmosphere to be 12.4 years (Myhre et al. 2013). This means that it is expected to take over 40 years for the perturbation resulting from a unit of CH_4 emitted today to decay to less than one percent of its initial size. The IPCC AR5 estimate of the perturbation lifetime of N_2O is 121 years. Impacts on temperature and other climatic variables will persist longer than the elevated concentrations due to the inertia of the climate system.

[7] See also the OMB Response to Comments on SC-CO_2, which elaborates on the use of global values (pp. 30-32) and the selection of discount rates (pp. 20-25), available at: https://www.whitehouse.gov/sites/default/files/omb/inforeg/scc-response-to-comments-final-july-2015.pdf.

[8] The FUND model is the only one of the three IAMs that explicitly considers CH_4 and N_2O using a one-box atmospheric gas cycle models for these gases, with geometric decay towards pre-industrial levels, based on the

Therefore, to estimate the SC-CH_4 and SC-N_2O, Marten et al. (2015) applied a one-box atmospheric gas cycle model to explicitly consider the path of additional radiative forcing from a CH_4 or N_2O perturbation, which is then added to the exogenous non-CO_2 radiative forcing projection to estimate the incremental damages compared to the baseline. The one-box atmospheric gas cycle model appended to DICE and PAGE used exponential decay functions to project atmospheric CH_4 and N_2O concentrations from the CH_4 and N_2O emissions projections, respectively, in the five socio-economic-emissions scenarios. They set the average lifetime of CH_4 and N_2O to 12 and 114 years, respectively, following the findings of the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report (AR4) (Forster et al. 2007). The direct radiative forcing associated with the atmospheric CH_4 and N_2O concentration was estimated using the functional relationships for each of these gases presented in the IPCC's Third Assessment Report (TAR) (Ramaswamy et al. 2001) and used in AR4. To account for the indirect effects of CH_4 as a precursor for tropospheric ozone and stratospheric water vapor, Marten et al. followed the approach of the IPCC in AR4 of increasing the direct radiative forcing of CH_4 by 40 percent.

The second modeling modification was needed because the SC-CO_2 modeling exercise assumed that overall radiative forcing from non-CO_2 sources remains constant past 2100 without specifying the projections for individual GHGs that were implicit in that assumption. This broad assumption was sufficient for the purposes of estimating the SC-CO_2; however, estimating the SC-CH_4 and SC-N_2O requires explicit projections of baseline CH_4 and N_2O emissions to determine the atmospheric concentration and radiative forcing off of which to compare the perturbation. Marten et al. (2015) chose to interpret the SC-CO_2 assumption for non-CO_2 radiative forcing past 2100 as applying to each gas individually, such that the emissions of each gas fall to their respective rate of atmospheric decay. This has the effect of holding global mean radiative forcing due to atmospheric CH_4 or N_2O constant past 2100. Marten et al. showed that, due to the relatively short lifetime of CH_4, alternative methods for extrapolating CH_4 emissions past 2100 have only a negligible effect (less than 0.5 percent) on the SC-CH_4. For the longer-lived gas N_2O, Marten et al. found the difference in the SC-N_2O estimates across the alternative methods to be less than 1 percent, even for emissions as far out as 2045, and found the projections to be equivalent to two significant digits.

III. Results

The SC-CH_4 and SC-N_2O estimates are presented in Table 1.[9] Following the same approach as with SC-CO_2, values for 2010, 2020, 2030, 2040, and 2050 are calculated by 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

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IPCC's Third Assessment Report (TAR) (Ramaswamy et al. 2001). FUND augments the TAR expression for the additional radiative forcing from CH_4 to account for the influences of stratospheric water vapor and tropospheric ozone changes.

[9] The Marten et al. (2015) estimates in this table and the remainder of the document have been adjusted to reflect the minor July 2015 technical corrections to the SC-CO_2 estimates. See Corrigendum to Marten et al. for more details, available at: http://www.tandfonline.com/doi/abs/10.1080/14693062.2015.1070550.

are calculated using linear interpolation. The full set of annual SC-CH_4 and SC-N_2O estimates between 2010 and 2050, and a detailed set of percentiles by model and scenario combination and additional summary statistics for 2020, are reported in Appendix Add-A. The full set of model results are available on the OMB website.[10]

Although a direct comparison of the estimates in Table 1 with all of the other published estimates is difficult, given the differences in the models and socioeconomic and emissions scenarios, results from three relatively recent studies offer a better basis for comparison (Hope 2006, Marten and Newbold 2012, Waldhoff et al. 2014). In general, the SC-CH_4 and SC-N_2O estimates in Table 1 are higher than previous estimates. The higher SC-CH_4 estimates are partially driven by the higher effective radiative forcing due to the inclusion of indirect effects from CH_4 emissions in the modeling. Similar to other recent studies, the directly modeled SC-CH_4 and SC-N_2O estimates in Table 1 are higher than the GWP-weighted SC-CO_2 estimates. A more detailed discussion comparing recent estimates of the SC-CH_4 and SC-N_2O can be found in Marten et al. (2015).

Table 1: SC-CH_4 and SC-N_2O Estimates (in 2007 dollars per metric ton)[11]

	SC-CH_4				SC-N_2O			
Year	5% Average	**3% Average**	2.5% Average	High Impact (3% 95th)	5% Average	**3% Average**	2.5% Average	High Impact (3% 95th)
2010	370	**870**	1,200	2,400	3,400	**12,000**	18,000	31,000
2015	450	**1,000**	1,400	2,800	4,000	**13,000**	20,000	35,000
2020	540	**1,200**	1,600	3,200	4,700	**15,000**	22,000	39,000
2025	650	**1,400**	1,800	3,700	5,500	**17,000**	24,000	44,000
2030	760	**1,600**	2,000	4,200	6,300	**19,000**	27,000	49,000
2035	900	**1,800**	2,300	4,900	7,400	**21,000**	29,000	55,000
2040	1,000	**2,000**	2,600	5,500	8,400	**23,000**	32,000	60,000
2045	1,200	**2,300**	2,800	6,100	9,500	**25,000**	34,000	66,000
2050	1,300	**2,500**	3,100	6,700	11,000	**27,000**	37,000	72,000

The estimates in Table 1 suggest the social cost of CH_4 emissions in 2020 is 26-46 times higher than for CO_2, with the larger difference occurring at higher discount rates.[12] For emissions in 2050 the SC-CH_4 is 31-52 times higher than the SC-CO_2. These ratios can be directly compared to the GWP, for which the IPCC

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

[11] To maintain consistency with the current SC-CO_2 TSD, values in this Addendum are presented in 2007 dollars. The SC-CH_4 estimates presented here are also rounded to two significant digits. The unrounded estimates (available on OMB's website) can be adjusted to current year dollars for use in RIAs using the GDP Implicit Price Deflator (available at http://www.bea.gov/iTable/index_nipa.cfm).

[12] This range of estimates of the global damage potential of CH_4 relative to CO_2 in 2020, and the same range for the N_2O results below, is calculated by dividing the (unrounded) SC-CH_4 estimate for each discount rate by the corresponding (unrounded) estimate of SC-CO_2.

AR4 100-year GWP of CH_4 was 25[13], to see how the GWP-based approach discussed above will likely provide an underestimate of the value of CH_4 emission changes particularly for higher discount rates and future emissions years in this application. Similarly, the estimates in Table 1 suggest the social cost of N_2O emissions in 2020 is 318-399 times higher than for CO_2, with the larger difference occurring at higher discount rates. For emissions in 2050 the SC-N_2O is 339-416 times higher than the SC-CO_2. Similar to the case for CH_4, these ratios can be directly compared to the GWP, for which the IPCC AR4 100-year GWP of N2O was 298, to see how the GWP-based approach discussed above will likely provide an underestimate of the value of N_2O emission changes particularly for higher discount rates and future emissions years in this application.

As was the case with SC-CO_2, the SC-CH_4 and SC-N_2O increase 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. Table 2 illustrates how the growth rate for the SC-CH_4 and SC-N_2O estimates varies over time.

Table 2: Average Annual Growth Rates of SC-CH_4 and SC-N_2O Estimates between 2010 and 2050

	SC-CH_4				SC-N_2O			
Average Annual Growth Rate (%)	5% Average	**3% Average**	2.5% Average	High Impact (3% 95th)	5% Average	**3% Average**	2.5% Average	High Impact (3% 95th)
2010-2020	4.6%	**3.8%**	3.3%	3.3%	3.8%	**2.5%**	2.2%	2.6%
2020-2030	4.1%	**3.3%**	2.5%	3.1%	3.4%	**2.7%**	2.3%	2.6%
2030-2040	3.2%	**2.5%**	3.0%	3.1%	3.3%	**2.1%**	1.9%	2.2%
2040-2050	3.0%	**2.5%**	1.9%	2.2%	3.1%	**1.7%**	1.6%	2.0%

The application of direct estimates of the SC-CH_4 and SC-N_2O to benefit-cost analysis of a regulatory action is analogous to the use of the SC-CO_2 estimates. The future monetized value of emission reductions in each year (the SC-CH_4 or SC-N_2O 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 discussed in the SC-CO_2 TSD, damages from future emissions should be discounted to the base year of the analysis at the same rate as that used to calculate the SC-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 using the same rate. The SC-CH_4 and SC-N_2O estimates would be applied in the same way to calculate climate-related costs of a rulemaking that leads to an increase in CH_4 or N_2O emissions, respectively.

IV. Treatment of Uncertainty

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[13] The Marten et al. (2015) estimates are based on the conclusions presented in IPCC AR4 (Forster et al. 2007), which was the latest assessment available when they conducted their modeling and analysis, and therefore GWP estimates based on the same assumptions would provide the most consistent comparison.

Given the consistency with the $SC\text{-}CO_2$ methodology, the IWG considered various sources of uncertainty in the $SC\text{-}CH_4$ and $SC\text{-}N_2O$ through a combination of a multi-model ensemble, probabilistic analysis, and scenario analysis. The outcome of accounting for various sources of uncertainty using these approaches is a frequency distribution of the $SC\text{-}CH_4$ and $SC\text{-}N_2O$ 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.

Figure 1 presents the frequency distribution of the $SC\text{-}CH_4$ estimates for emissions in 2020 for each of the three discount rates.[14] Figure 2 presents the frequency distribution of the $SC\text{-}N_2O$ estimates for emissions in 2020 for each of the three discount rates.[15] Each distribution in Figures 1 and 2 represents 150,000 estimates based on 10,000 simulations for each combination of the three models and five socioeconomic and emissions scenarios. As with the $SC\text{-}CO_2$, 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 estimates and other quantified sources of uncertainty, the bars below the frequency distributions provide a symmetric (5th to 95th percentile) representation of quantified variability in the $SC\text{-}CH_4$ and $SC\text{-}N_2O$ estimates conditioned on each discount rate. The full set of $SC\text{-}CH_4$ and $SC\text{-}N_2O$ results through 2050 is available on OMB's website. This may be useful to analysts in situations that warrant additional quantitative uncertainty analysis. See OMB Circular A-4 for guidance and discussion of best practices in conducting uncertainty analysis in RIAs.

Figure 1: Frequency Distribution of $SC\text{-}CH_4$ Estimates for 2020 (in 2007$ per metric ton CH_4)

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[14] 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 limits of the horizontal axis are truncated, such that 0.02 to 0.11 percent of the $SC\text{-}CH_4$ frequency distribution lies below the lowest bin presented and 0.34 to 3.1 percent of the frequency distribution lies above the highest bin presented, depending on the discount rate.

[15] Although the distributions in Figure 2 are based on the full set of model results (150,000 estimates for each discount rate), for display purposes the limits of the horizontal axis are truncated, such that 0.03 to 0.10 percent of the $SC\text{-}N_2O$ frequency distribution lies below the lowest bin presented and 0.04 to 3.00 percent of the frequency distribution lies above the highest bin presented, depending on the discount rate.

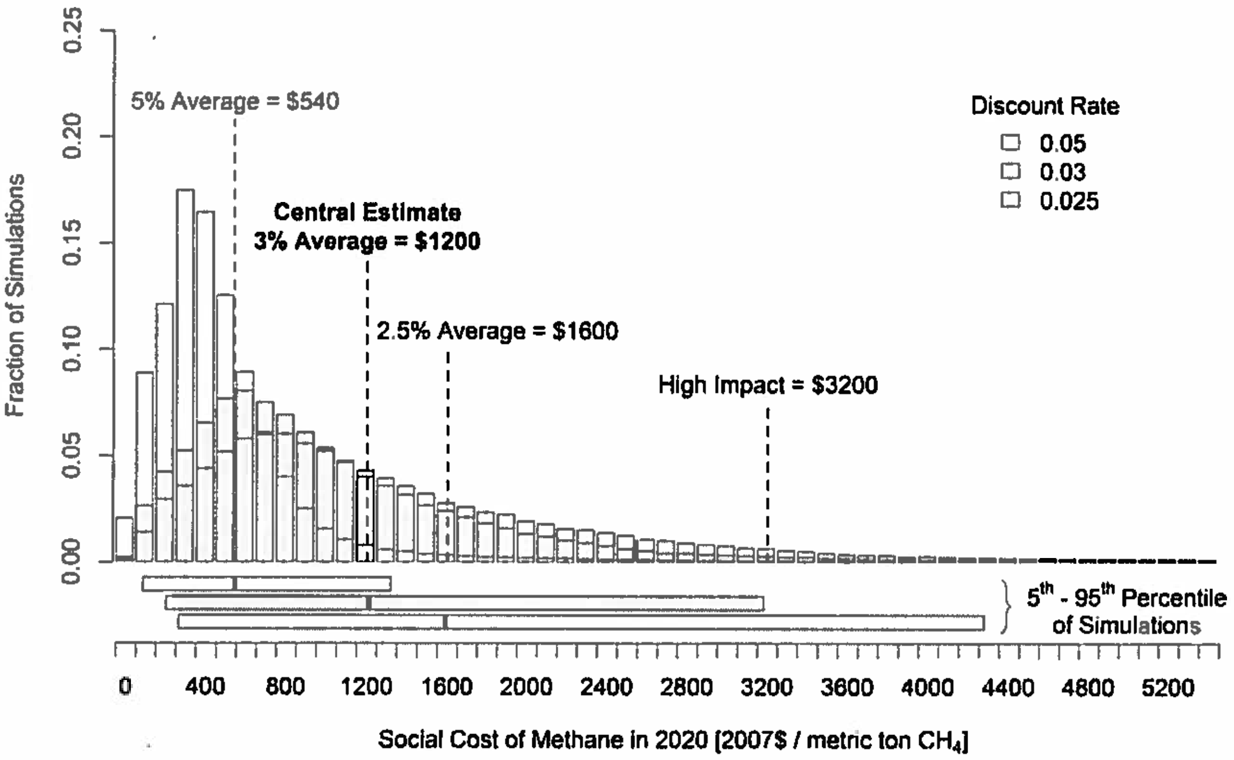
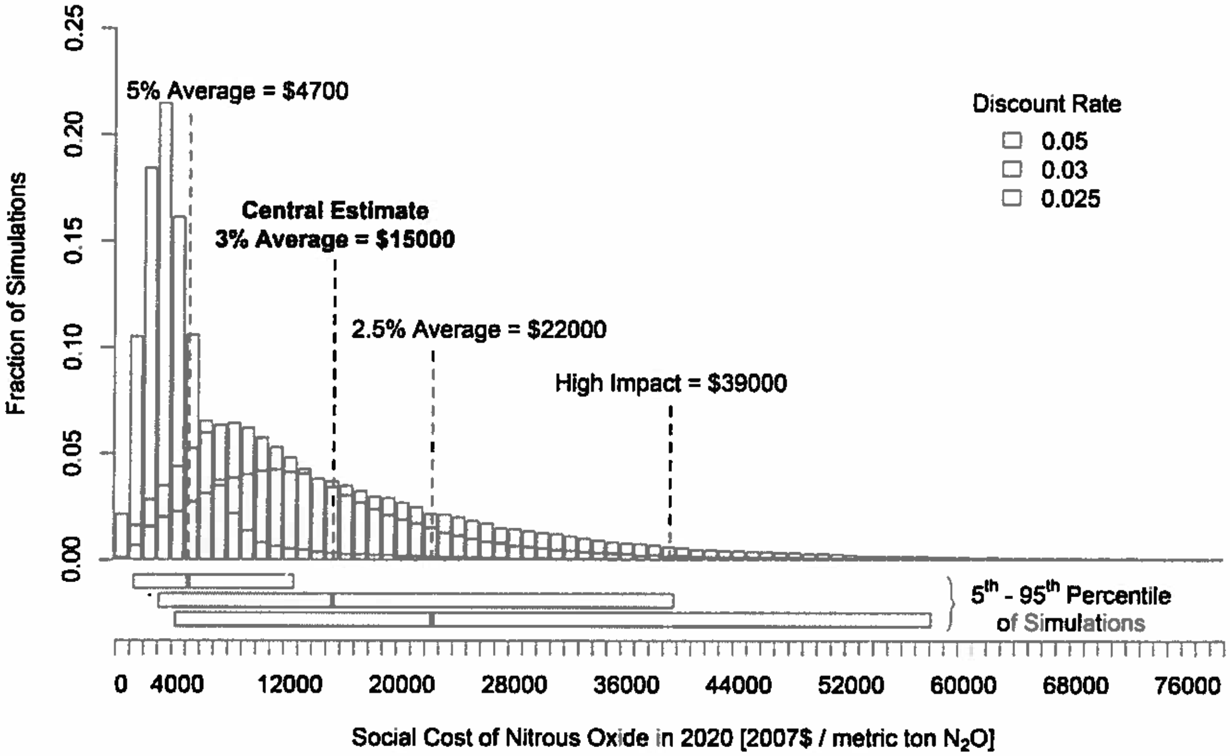


Figure 2: Frequency Distribution of SC-N_2O Estimates for 2020 (in 2007$ per metric ton N_2O)



V. Limitations and Research Gaps

Given the consistency in underlying modeling methods and inputs, the SC-CH_4 and SC-N_2O estimates presented above share many of the same uncertainties and limitations as the SC-CO_2 estimates. Thus, they are presented with a clear understanding that they should be updated over time to reflect increasing knowledge of the science and economics of climate impacts. A number of areas where additional research is needed are discussed in the SC-CO_2 TSD. Here we discuss a few additional limitations that are specific to the SC-CH_4 and SC-N_2O estimates.

First, as discussed above, the one-box atmospheric gas cycle model used to explicitly consider the path of additional radiative forcing from CH_4 and N_2O perturbations in DICE and PAGE followed the findings of IPCC AR4, which was the latest assessment report at the time of the study. Updating the approach to include new findings from the IPCC Fifth Assessment Report (AR5) is expected to increase the SC-CH_4 estimates, such that the relationship between the direct SC-CH4 estimates and the GWP-based approach, as discussed in Section 3, are expected to hold. Updating the approach for the SC-N_2O is expected to either reduce the SC-N_2O estimates or to leave them nearly unchanged, depending on which approach to including climate-carbon feedbacks is used. The AR5 update most relevant for the SC-CH_4 is the increase of the adjustment factor to account for tropospheric ozone and stratospheric water vapor from 40 to 65 percent. Additionally, AR5 updated the perturbation lifetime of CH_4 from 12 years to 12.4 years and also presented GWPs that included the CO_2 oxidation product of fossil-fuel derived CH_4. For N_2O, the AR5 analysis included the effects of a reduction in CH_4 of 0.36 molecules for every additional N_2O molecule in the atmosphere because of N_2O impacts on stratospheric ozone, UV fluxes, and hydroxyl radical levels, and updated the perturbation lifetime of N_2O from 114 to 121 years. In addition, the AR5 assessment updated CH_4, N_2O, and CO_2 radiative efficiencies by less than 3 percent (due mainly to changes in background concentrations), presented an additional GWP that included an adjustment for climate-carbon feedbacks, and updated the impulse response function used for approximating CO_2 lifetimes. These updates led to GWPs for CH_4 presented by AR5 ranging from 28-36, compared to a GWP of 25 in AR4, and GWPs for N_2O ranging from 265-298 compared to a GWP of 298 in AR4 (Myhre et al. 2013).

Second, the direct health and welfare effects of tropospheric ozone production resulting from CH_4 emissions are not captured in the IAM damage functions and, thus, are not included in the SC-CH_4 estimates presented above. The global monetized benefit of the health effects resulting from ozone reduction due to CH_4 mitigation have been estimated in several studies (e.g., Anenberg et al. 2012, Shindell et al. 2012). A recent paper published in the peer-reviewed scientific literature presented a range of estimates of the monetized ozone-related mortality benefits of reducing CH_4 emissions using a methodology consistent in some (but not all) aspects with the modeling underlying the SC-CO_2 and SC-CH_4 estimates discussed above (Sarofim et al. 2015). Similar to previous studies, under their base case assumptions using a 3 percent discount rate, Sarofim et al. find global ozone-related mortality benefits of CH_4 emissions reductions to be $790 per metric ton of CH_4 in 2020, with 10.6 percent, or $80, of this amount resulting from mortality reductions in the United States. Additional welfare impacts of ozone, not included in this estimate, stem from damage to plants, which can lead to reductions in both crop yield and carbon sequestration by natural systems (Felzer et al. 2005, Shindell et al. 2012). Both of these impacts would suggest additional damages associated with CH_4 emissions that are not included in the SC-CH_4 estimates.

Third, the SC-CH_4 estimates do not reflect that CH_4 emissions lead to a reduction in atmospheric oxidants such as hydroxyl radicals. These oxidants are important for the conversion of sulfur dioxide into sulfates. Therefore, CH_4 emissions can suppress sulfate formation, leading to an increase in radiative forcing but a decrease in particulate matter and resulting health impacts (Shindell et al. 2009, Fry et al. 2012). The net effect of these offsetting impacts is not clear.

Fourth, the SC-CH_4 estimates do not account for impacts associated with CO_2 produced from CH_4 oxidizing in the atmosphere (Boucher et al. 2009); the inclusion of these impacts would increase the SC-CH_4 estimates.

Finally, in addition to the climate impacts of N_2O on radiative forcing due to changes in CH_4 concentrations resulting from effects on stratospheric ozone, UV fluxes, and hydroxyl radical levels discussed above, these changes may also have effects on the atmospheric behavior of other pollutants as well as direct effects on human health. These effects are not currently included in the calculation of the SC-N_2O.

VI. Concluding Remarks

As directed by Executive Orders 12866 and 13563, federal agencies must use the best available scientific, technical, economic, and other information to quantify the costs and benefits of regulatory actions. Rigorous evaluation of costs and benefits has been a core tenet of the rulemaking process for decades. The estimates presented in this addendum offer a tool for improving the analyses of regulatory actions that are projected to influence CH_4 or N_2O emissions without introducing inconsistency with the manner in which CO_2 emission changes are valued. These estimates can and should be updated if and when the modeling assumptions underlying the SC-CO_2 estimates are updated to reflect the conclusions of IPCC AR5 or other evolving scientific and economic knowledge.

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Appendix Add-A

Table A1: Annual SC-CH$_4$ and SC-N$_2$O Values: 2010-2050 (2007$/metric ton)

	SC-CH$_4$				SC-N$_2$O			
Year	5% Average	**3% Average**	2.5% Average	High Impact (3% 95th)	5% Average	**3% Average**	2.5% Average	High Impact (3% 95th)
2010	370	**870**	1.200	2.400	3.400	**12.000**	18.000	31.000
2011	380	**910**	1,200	2,500	3,500	**12,000**	18,000	32,000
2012	400	**940**	1,300	2,600	3,700	**12,000**	19,000	33,000
2013	420	**970**	1,300	2,700	3,800	**13,000**	19,000	34,000
2014	440	**1,000**	1,300	2,700	3,900	**13,000**	20,000	34,000
2015	450	**1,000**	1,400	2,800	4,000	**13,000**	20,000	35,000
2016	470	**1,100**	1,400	2,900	4,200	**14,000**	20,000	36,000
2017	490	**1,100**	1,500	3,000	4,300	**14,000**	21,000	37,000
2018	510	**1,100**	1,500	3,000	4,400	**14,000**	21,000	38,000
2019	520	**1,200**	1,500	3,100	4,600	**15,000**	22,000	38,000
2020	540	**1,200**	1,600	3,200	4,700	**15,000**	22,000	39,000
2021	560	**1,200**	1,600	3,300	4,900	**15,000**	23,000	40,000
2022	590	**1,300**	1,700	3,400	5,000	**16,000**	23,000	41,000
2023	610	**1,300**	1,700	3,500	5,200	**16,000**	23,000	42,000
2024	630	**1,400**	1,800	3,600	5,400	**16,000**	24,000	43,000
2025	650	**1,400**	1,800	3,700	5,500	**17,000**	24,000	44,000
2026	670	**1,400**	1,900	3,800	5,700	**17,000**	25,000	45,000
2027	700	**1,500**	1,900	3,900	5,900	**17,000**	25,000	46,000
2028	720	**1,500**	2,000	4,000	6,000	**18,000**	26,000	47,000
2029	740	**1,600**	2,000	4,100	6,200	**18,000**	26,000	48,000
2030	760	**1,600**	2,000	4,200	6,300	**19,000**	27,000	49,000
2031	790	**1,600**	2,100	4,300	6,500	**19,000**	27,000	50,000
2032	820	**1,700**	2,100	4,500	6,800	**19,000**	28,000	51,000
2033	850	**1,700**	2,200	4,600	7,000	**20,000**	28,000	52,000
2034	880	**1,800**	2,200	4,700	7,200	**20,000**	29,000	54,000
2035	900	**1,800**	2,300	4,900	7,400	**21,000**	29,000	55,000
2036	930	**1,900**	2,400	5,000	7,600	**21,000**	30,000	56,000
2037	960	**1,900**	2,400	5,100	7,800	**21,000**	30,000	57,000
2038	990	**2,000**	2,500	5,200	8,000	**22,000**	31,000	58,000
2039	1,000	**2,000**	2,500	5,400	8,200	**22,000**	31,000	59,000
2040	1,000	**2,000**	2,600	5,500	8,400	**23,000**	32,000	60,000
2041	1,100	**2,100**	2,600	5,600	8,600	**23,000**	32,000	61,000
2042	1,100	**2,100**	2,700	5,700	8,800	**23,000**	33,000	62,000
2043	1,100	**2,200**	2,700	5,800	9,100	**24,000**	33,000	64,000
2044	1,200	**2,200**	2,800	5,900	9,300	**24,000**	34,000	65,000
2045	1,200	**2,300**	2,800	6,100	9,500	**25,000**	34,000	66,000
2046	1,200	**2,300**	2,900	6,200	9,800	**25,000**	35,000	67,000
2047	1,300	**2,400**	2,900	6,300	10,000	**26,000**	35,000	68,000
2048	1,300	**2,400**	3,000	6,400	10,000	**26,000**	36,000	69,000
2049	1,300	**2,500**	3,000	6,500	10,000	**26,000**	36,000	71,000
2050	1,300	**2,500**	3,100	6,700	11,000	**27,000**	37,000	72,000

Table A2: 2020 Global SC-CH_4 Estimates at 2.5 Percent Discount Rate (2007$/metric ton CH_4)

Percentile	1st	5th	10th	25th	50th	Avg	75th	90th	95th	99th
Scenario[16]					PAGE					
IMAGE	120	220	300	520	1100	2200	2500	5500	8300	14000
MERGE Optimistic	90	160	220	380	790	1600	1900	4200	6400	11000
MESSAGE	110	190	260	450	940	2000	2200	5100	7900	14000
MiniCAM Base	100	190	260	450	940	1900	2200	4900	7300	13000
5th Scenario	64	120	170	290	590	1400	1500	3600	5900	12000

Scenario					DICE					
IMAGE	460	580	670	880	1200	1400	1800	2600	3000	3500
MERGE Optimistic	330	420	490	640	890	1000	1300	1800	2100	2400
MESSAGE	420	540	630	820	1100	1300	1700	2300	2600	3100
MiniCAM Base	400	520	600	790	1100	1300	1700	2400	2800	3300
5th Scenario	360	460	530	680	920	1100	1300	1900	2200	2600

Scenario					FUND					
IMAGE	170	450	610	980	1600	1900	2400	3600	4400	6500
MERGE Optimistic	230	500	650	990	1500	1800	2300	3300	4100	6400
MESSAGE	180	430	580	920	1400	1700	2200	3100	3700	5500
MiniCAM Base	230	480	640	1000	1600	1800	2400	3500	4300	6500
5th Scenario	-10	260	390	670	1100	1300	1700	2400	3000	4400

Table A3: 2020 Global SC-CH_4 Estimates at 3 Percent Discount Rate (2007$/metric ton CH_4)

Percentile	1st	5th	10th	25th	50th	Avg	75th	90th	95th	99th
Scenario					PAGE					
IMAGE	86	160	220	380	800	1700	1900	4200	6500	12000
MERGE Optimistic	64	120	160	280	590	1300	1400	3300	5100	8900
MESSAGE	77	140	200	350	720	1600	1700	4000	6300	12000
MiniCAM Base	74	140	190	330	690	1500	1600	3700	5700	10000
5th Scenario	44	91	130	230	470	1100	1100	2800	4700	9400

Scenario					DICE					
IMAGE	360	460	530	690	940	1100	1400	1900	2100	2500
MERGE Optimistic	270	340	400	510	700	790	1000	1300	1500	1800
MESSAGE	350	440	510	660	900	1000	1300	1700	2000	2300
MiniCAM Base	310	400	460	600	830	960	1200	1700	2000	2300
5th Scenario	290	370	420	540	720	820	1000	1400	1600	1900

Scenario					FUND					
IMAGE	160	370	490	760	1200	1400	1800	2500	3100	4600
MERGE Optimistic	200	400	520	770	1200	1400	1700	2400	3000	4700
MESSAGE	160	370	470	720	1100	1300	1600	2200	2700	4000
MiniCAM Base	200	400	510	770	1200	1300	1700	2500	3000	4600
5th Scenario	41	240	340	540	840	980	1200	1700	2100	3000

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[16] See 2010 SC-CO_2 TSD for a description of these scenarios.

Table A4: 2020 Global SC-CH_4 Estimates at 5 Percent Discount Rate (2007$/metric ton CH_4)

Percentile	1st	5th	10th	25th	50th	Avg	75th	90th	95th	99th
Scenario	PAGE									
IMAGE	26	58	85	160	330	770	810	2000	3100	6200
MERGE Optimistic	18	42	61	110	240	570	600	1400	2300	4600
MESSAGE	23	53	79	150	310	740	770	1900	3000	6100
MiniCAM Base	20	47	68	130	270	640	670	1600	2600	5100
5th Scenario	11	34	53	100	220	560	550	1400	2300	4900

Scenario	DICE									
IMAGE	200	250	290	360	460	490	610	770	850	950
MERGE Optimistic	160	200	220	270	350	380	470	590	650	730
MESSAGE	210	260	290	360	460	500	610	760	840	940
MiniCAM Base	170	210	240	300	390	420	520	660	740	830
5th Scenario	170	210	240	290	370	400	490	610	680	760

Scenario	FUND									
IMAGE	110	200	250	350	500	570	700	950	1100	1700
MERGE Optimistic	110	200	250	350	500	570	700	960	1200	1800
MESSAGE	110	200	240	340	490	550	680	910	1100	1600
MiniCAM Base	120	200	250	340	490	550	680	920	1100	1600
5th Scenario	73	150	200	280	390	430	540	700	820	1100

Table A5: 2020 Global SC-N_2O Estimates at 2.5 Percent Discount Rate (2007$/metric ton N_2O)

Percentile	1st	5th	10th	25th	50th	Avg	75th	90th	95th	99th
Scenario	PAGE									
IMAGE	2100	3900	5300	9300	20000	36000	44000	92000	130000	200000
MERGE Optimistic	1400	2500	3500	6100	13000	24000	30000	62000	91000	140000
MESSAGE	1400	2600	3600	6400	14000	28000	32000	71000	110000	180000
MiniCAM Base	1700	3100	4300	7600	16000	30000	37000	77000	110000	170000
5th Scenario	650	1300	1900	3400	7500	18000	19000	47000	75000	150000

Scenario	DICE									
IMAGE	8900	11000	13000	17000	23000	26000	33000	43000	49000	56000
MERGE Optimistic	5600	7100	8100	10000	14000	15000	19000	25000	28000	32000
MESSAGE	6400	8000	9200	12000	16000	18000	23000	30000	34000	40000
MiniCAM Base	7500	9600	11000	14000	20000	22000	28000	38000	43000	49000
5th Scenario	4800	6100	7000	8900	12000	14000	18000	25000	29000	34000

Scenario	FUND									
IMAGE	3300	6300	8200	13000	20000	24000	31000	44000	54000	75000
MERGE Optimistic	3600	6400	8200	12000	18000	21000	27000	37000	44000	65000
MESSAGE	2700	5500	7100	11000	16000	19000	24000	34000	40000	56000
MiniCAM Base	3500	6500	8200	12000	19000	22000	29000	41000	49000	71000
5th Scenario	790	3300	4500	7300	12000	14000	18000	27000	32000	44000

Table A6: 2020 Global SC-N_2O Estimates at 3 Percent Discount Rate (2007$/metric ton N_2O)

Percentile	1st	5th	10th	25th	50th	Avg	75th	90th	95th	99th
Scenario					PAGE					
IMAGE	1400	2500	3500	6200	13000	25000	30000	65000	95000	150000
MERGE Optimistic	910	1700	2300	4100	8900	17000	21000	45000	67000	100000
MESSAGE	930	1800	2500	4400	9600	20000	23000	51000	78000	140000
MiniCAM Base	1100	2000	2800	4900	11000	21000	25000	54000	79000	130000
5th Scenario	440	910	1300	2400	5400	13000	14000	34000	54000	110000

Scenario					DICE					
IMAGE	6000	7600	8700	11000	15000	17000	21000	28000	31000	35000
MERGE Optimistic	3900	5000	5600	7200	9500	10000	13000	17000	19000	21000
MESSAGE	4600	5700	6600	8400	11000	12000	16000	20000	23000	26000
MiniCAM Base	5000	6400	7300	9400	13000	14000	18000	24000	27000	30000
5th Scenario	3400	4300	4900	6200	8300	9600	12000	16000	19000	22000

Scenario					FUND					
IMAGE	2400	4500	5700	8400	13000	15000	19000	28000	33000	47000
MERGE Optimistic	2600	4500	5600	8100	12000	14000	17000	24000	29000	43000
MESSAGE	2000	4000	5000	7300	11000	13000	16000	22000	26000	37000
MiniCAM Base	2600	4500	5700	8300	12000	14000	18000	26000	31000	45000
5th Scenario	790	2500	3300	5200	7900	9100	12000	17000	20000	28000

Table A7: 2020 Global SC-N_2O Estimates at 5 Percent Discount Rate (2007$/metric ton N_2O)

Percentile	1st	5th	10th	25th	50th	Avg	75th	90th	95th	99th
Scenario					PAGE					
IMAGE	330	680	950	1700	3800	8300	9200	21000	33000	61000
MERGE Optimistic	220	450	640	1200	2600	5700	6300	15000	23000	42000
MESSAGE	250	530	750	1400	3100	6900	7500	18000	28000	54000
MiniCAM Base	250	520	730	1300	3000	6500	7200	17000	26000	48000
5th Scenario	110	290	440	830	1900	4700	4800	12000	20000	42000

Scenario					DICE					
IMAGE	2100	2600	2900	3600	4600	4900	6000	7500	8200	9200
MERGE Optimistic	1500	1800	2000	2500	3200	3400	4200	5100	5600	6200
MESSAGE	1800	2200	2500	3100	3900	4200	5100	6300	7000	7700
MiniCAM Base	1700	2100	2300	2900	3700	4000	4900	6100	6800	7500
5th Scenario	1400	1700	1900	2300	2900	3200	3900	4900	5400	6100

Scenario					FUND					
IMAGE	890	1500	1900	2600	3700	4200	5200	7000	8400	12000
MERGE Optimistic	900	1500	1800	2500	3500	4100	5000	6800	8200	12000
MESSAGE	830	1400	1800	2400	3400	3800	4700	6300	7500	11000
MiniCAM Base	980	1500	1800	2500	3500	3900	4800	6500	7800	12000
5th Scenario	540	1100	1300	1800	2500	2800	3500	4600	5300	7200

Table A8: Additional Summary Statistics of 2020 Global SC-CH_4 Estimates

Discount rate:	5.0%				3.0%				2.5%			
Statistic:	Mean	Variance	Skewness	Kurtosis	Mean	Variance	Skewness	Kurtosis	Mean	Variance	Skewness	Kurtosis
DICE	440	28000	1	0	930	210000	1	1	1200	420000	1	1
PAGE	650	1200000	4	26	1400	4400000	3	15	1800	6700000	3	13
FUND	530	160000	44	5900	1300	7800000	36	12000	1700	29000000	-4	11000

Table A9: Additional Summary Statistics of 2020 Global SC-N_2O Estimates

Discount rate:	5.0%				3.0%				2.5%			
Statistic:	Mean	Variance	Skewness	Kurtosis	Mean	Variance	Skewness	Kurtosis	Mean	Variance	Skewness	Kurtosis
DICE	3900	2300000	1	0	13000	40000000	2	13	19000	110000000	4	67
PAGE	6400	97000000	4	17	19000	690000000	3	9	27000	1300000000	3	8
FUND	3700	5400000	-2	260	13000	120000000	-1	360	20000	370000000	-2	540