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

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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

[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]

[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

[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

[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-CO_2 methodology, the IWG considered various sources of uncertainty in the SC-CH_4 and SC-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-CH_4 and SC-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-CH_4 estimates for emissions in 2020 for each of the three discount rates.[14] Figure 2 presents the frequency distribution of the SC-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-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-CH_4 and SC-N_2O estimates conditioned on each discount rate. The full set of SC-CH_4 and SC-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-CH_4 Estimates for 2020 (in 2007$ per metric ton CH_4)

[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-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-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.

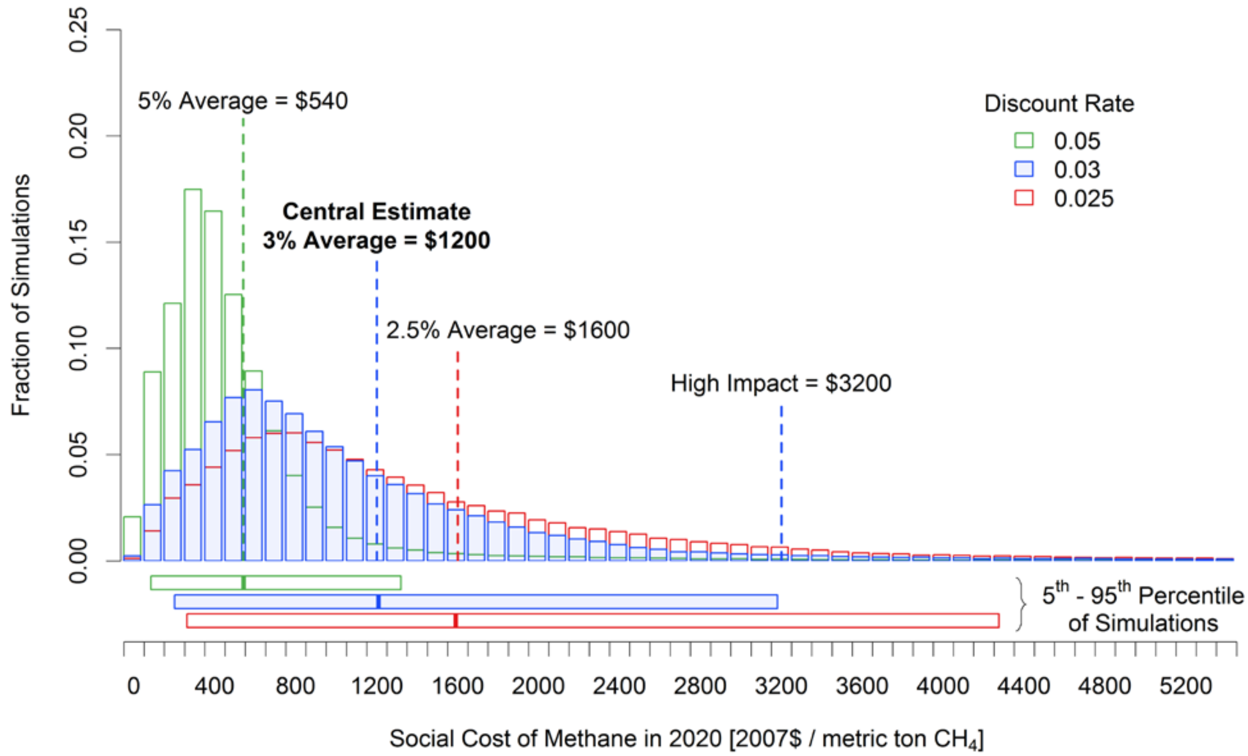
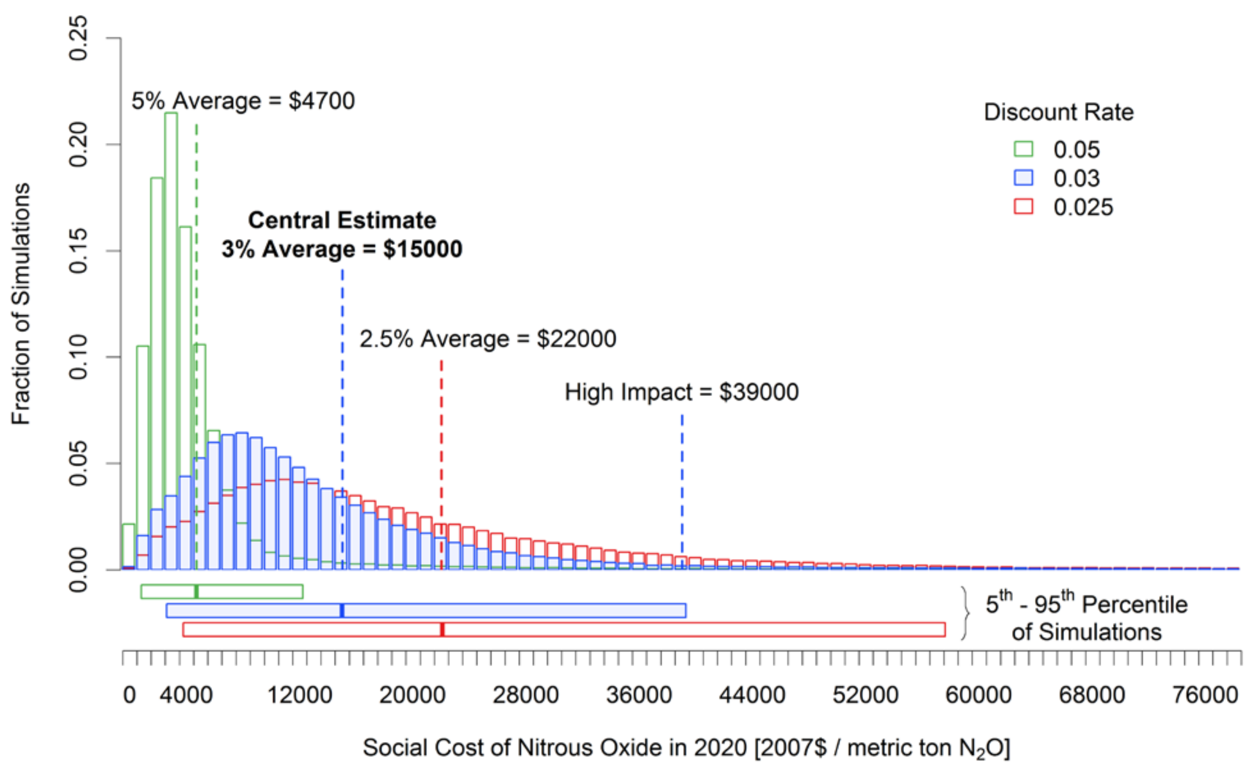


Figure 2: Frequency Distribution of SC-N_2O Estimates for 2020 (in 2007$ per metric ton N_2O)



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_2O Values: 2010-2050 (2007$/metric ton)

	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
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

[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