The Social Cost of Ozone-Related Mortality Impacts from Methane Emissions

Erin E. McDuffie\textsuperscript{1}, Marcus Sarofim\textsuperscript{2}, William Raich\textsuperscript{3}, Melanie A Jackson\textsuperscript{3}, Henry Roman\textsuperscript{4}, Karl Seltzer\textsuperscript{5}, Barron Henderson\textsuperscript{6}, Drew T. Shindell\textsuperscript{7}, Mei Collins\textsuperscript{3}, Jim Anderton\textsuperscript{3}, Sarah Barr\textsuperscript{1}, and Neal Fann\textsuperscript{1}

\textsuperscript{1}U.S. Environmental Protection Agency
\textsuperscript{2}United States Environmental Protection Agency
\textsuperscript{3}Industrial Economics, Incorporated
\textsuperscript{4}Industrial Economics, Inc.
\textsuperscript{5}U.S. EPA
\textsuperscript{6}Environmental Protection Agency
\textsuperscript{7}Duke University

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Abstract

Atmospheric methane directly affects surface temperatures and indirectly affects ozone, impacting human welfare, the economy, and environment. The social cost of methane (SC-CH\textsubscript{4}) metric estimates the costs associated with an additional marginal metric ton of emissions. Current SC-CH\textsubscript{4} estimates do not consider the indirect impacts associated with ozone production from changes in methane. We use global model simulations and a new BenMAP webtool to estimate respiratory-related deaths associated with increases in ozone from a pulse of methane emissions in 2020. By using an approach consistent with the current SC-CH\textsubscript{4} framework, we monetize and discount annual damages back to present day values. We estimate that the methane-ozone mechanism is attributable to 760 (95\% CI: 330-1200) respiratory-related deaths per million metric tons (MMT) of methane globally, for a global net present damage of $1700/mT (95\% CI: $710-$2600/mT CH\textsubscript{4}; 2\% Ramsey discount rate); this would double the current SC-CH\textsubscript{4} if included. These physical impacts are consistent with recent studies, but comparing direct costs is challenging. Economic damages are sensitive to uncertainties in the exposure and health risks associated with tropospheric ozone, assumptions about future projections of NO\textsubscript{x} emissions, socioeconomic conditions, and mortality rates, choice of discount rates, and other factors. Our estimates are most sensitive to uncertainties in ozone health risks. We also develop a reduced form model to test sensitivities to other parameters. The reduced form tool runs with a user-supplied emissions pulse, as well as socioeconomic and precursor projections, enabling future integration of the methane-ozone mechanism into the SC-CH\textsubscript{4} modeling framework.
a) Annual Global CH$_4$-O$_3$-Attributable Respiratory Mortality

b) Total CH$_4$-O$_3$-Attributable Respiratory Per Capita Mortality

c) CH$_4$-O$_3$ Net Present Value, by Region
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Erin E. McDuffie1, Marcus C. Sarofim1, William Raich2, Melanie Jackson2, Henry Roman2, Karl Seltzer3, Barron Henderson3, Drew T. Shindell4, Mei Collins5, Jim Anderton2, Sarah Barr1, Neal Fann5

1Office of Atmospheric Protection, Climate Change Division, U.S. Environmental Protection Agency, Washington, DC, USA
2Industrial Economics, Incorporated, Cambridge, MA, USA
3Office of Air Quality Planning and Standards, Air Quality Assessment Division, U.S. Environmental Protection Agency, Research Triangle Park, NC, USA
4Nicholas School of the Environment, Duke University, Durham, NC, USA
5Office of Air Quality Planning and Standards, Health and Environmental Impacts Division, U.S. Environmental Protection Agency, Research Triangle Park, NC, USA

Corresponding author: Erin E McDuffie (mcduffie.erin.e@epa.gov)

Key Points:

- Increases in mortality attributable to ozone produced from methane are not currently considered in the government’s social cost of methane
- Ozone from a 2020 methane emissions pulse results in 760 deaths per million metric ton and a net present value of $1700 per metric ton
- A reduced form tool is developed to assess uncertainties and facilitate additional social cost of methane calculations

Abstract:

Atmospheric methane directly affects surface temperatures and indirectly affects ozone, impacting human welfare, the economy, and environment. The social cost of methane (SC-CH4) metric estimates the costs associated with an additional marginal metric ton of emissions. Current SC-CH4 estimates do not consider the indirect impacts associated with ozone production from changes in methane. We use global model simulations and a new BenMAP webtool to estimate respiratory-related deaths associated with increases in ozone from a pulse of methane emissions in 2020. By using an approach consistent with the current SC-CH4 framework, we monetize and discount annual damages back to present day values. We estimate that the methane-ozone mechanism is attributable to 760 (95% CI: 330-1200) respiratory-related deaths per million metric tons (MMT) of methane globally, for a global net present damage of $1700/mT (95% CI: $710-$2600/mT CH4; 2% Ramsey discount rate); this would double the current SC-CH4 if included. These physical impacts are consistent with recent studies, but comparing direct costs is challenging. Economic damages are sensitive to uncertainties in the exposure and health risks associated with tropospheric ozone, assumptions about future projections of NOx emissions, socioeconomic conditions, and mortality rates, choice of discount rates, and other factors. Our estimates are most sensitive to uncertainties in ozone health risks. We also develop a reduced form model to test sensitivities to other parameters. The reduced form tool runs with a user-supplied emissions pulse, as well as socioeconomic and precursor projections, enabling future integration of the methane-ozone mechanism into the SC-CH4 modeling framework.
Plain Language Summary

The social cost of methane is used to assess the costs and benefits associated with emissions mitigation in U.S. regulations, in addition to other decision-making applications. The current social cost of methane used by the U.S. Government is $1500/metric ton of methane emissions. This estimate does not include damages related to deaths associated with changes in exposure to background ozone, resulting from increases in atmospheric methane. Using an approach consistent with the social cost of methane framework, we estimate that damages from the methane-ozone mechanism are $1700/metric ton, which, if included, would double the current social cost of methane. These costs have uncertainties related to the health risks associated with exposure to ozone, assumptions about future NOx emissions, choice of discount rates, and other factors. We also develop a reduced form model that allows rapid estimation of many of these sensitivities and enables consideration of this mechanism in the social cost methodology.

1. Introduction

Methane is emitted from a variety of natural and anthropogenic sources (e.g., agriculture, wetlands, oil and gas activities, coal mining, etc.) and is the second most important greenhouse gas (GHG) behind carbon dioxide (CO2), having contributed to roughly half a degree of present-day warming (and ~1/3 of total GHG-induced warming). Methane, however, has a shorter atmospheric lifetime than CO2 (a perturbation lifetime of ~12 years, contrasting with CO2’s lifetime of centuries to millennia), such that reductions in global methane emissions can lead to reductions in atmospheric concentrations in only a matter of years [IPCC, 2021]. Recently, under the Global Methane Pledge, over 150 participants agreed to reduce global methane emissions by 30% by 2030 relative to 2020 levels, which has been projected to decrease mean midcentury global surface warming by 0.2 °C [CCAC Secretariat, 2021]. The social cost of methane (SC-CH4) [Errickson et al., 2021; Marten and Newbold, 2012; Shindell et al., 2017] has been used to value these and other types of direct climate benefits associated with marginal methane emission changes, most recently valued at roughly $1500 (2020$, 2020 emissions, 3% economic discount rate) [Interagency Working Group on Social Cost of Greenhouse Gases (IWG), 2021] or $1600 (2020$, 2020 emissions, 2% Ramsey discounting rate) [EPA, 2022] per metric ton of methane (mT CH4).

These estimates include damages to human health, agriculture, energy, and labor associated with projected increases in surface temperatures and other climate responses to changes in atmospheric methane concentrations.

In addition to these direct impacts, methane also contributes to the chemical formation of tropospheric ozone. Ozone in the troposphere is a GHG and air pollutant, responsible for over 11% of chronic respiratory deaths attributable to outdoor air pollution worldwide each year [GBD 2019 Risk Factor Collaborators, 2020], as well as global agricultural crop damages of over $34 billion [in 2010 in 2015$, Sampredo et al., 2020]. Ozone formation in the troposphere occurs from the reaction of volatile organic compounds (VOCs) or carbon monoxide with nitrogen oxides (NOx = NO + NO2) in the presence of sunlight. Methane’s 12-year lifetime is much longer than the hour-to-week lifetimes of most other organic ozone precursors. Therefore, methane becomes relatively well-mixed in the atmosphere and ozone production from methane’s oxidation contributes to ‘background’ levels of ozone, rather than localized production. While localized ozone production is an important consideration for regional air pollution mitigation policies, the United States Environmental Protection Agency (EPA) has long
recognized that methane mitigation is a poor candidate for addressing local air quality problems. Since
1977, the EPA has exempted methane from the definition of “volatile organic compound” on the
grounds that methane has “negligible photochemical reactivity.” [40 CFR 51.100(s)(1)]; “Recommended
Policy on Control of Volatile Organic Compounds,” [42 Fed. Reg. 35314, July 8, 1977]. As a result, the
EPA does not regulate methane as part of its programs to implement the national ambient air quality
standards for ozone. The health effects of ozone, however, are determined by total tropospheric
concentrations, which are a combination of local/regional ozone production and the global background.
In contrast to localized ozone, changes in background ozone concentrations occur on time scales similar
to methane’s lifetime (e.g., ~12 years), are relatively insensitive to specific locations where emission
changes occur, and have been shown to respond linearly to changes in methane [e.g., West et al., 2006].
These large multi-year and global scale impacts make this methane-ozone mechanism a good candidate
for the social cost of carbon framework.

Previous studies [Anenberg et al., 2012; Sarofim et al., 2017; Shindell et al., 2012; West et al., 2006] have
leveraged the relative uniformity in the ozone response to methane changes to estimate global health
damages per metric ton of methane. These estimates are generally of the same magnitude as the
climate damages from the social cost of methane. Many of these and other studies have also estimated
methane-ozone damages from other effects, such as short-term health impacts (e.g., asthma-related
hospital visits) and agricultural crop losses, which can also account for a sizeable fraction of current SC-
CH₄ estimates [e.g., Sampedro et al., 2023; UNEP & CCAC, 2021]. Current SC-CH₄ values only account for
climate-driven damages from methane emissions, indicating that incorporating the global health and
monetary benefits from methane emissions-related ozone changes would be an important modification
to the social cost framework.

Most recently, the UN Environmental Program and Climate and Clean Air Coalition (UNEP/CCAC)
published the Global Methane Assessment report [UNEP/CCAC, 2021], which included estimates of the
physical and economic impacts to global mortality, morbidity, labor productivity, and agricultural yields
attributable to ozone produced from methane oxidation. Of these categories, the greatest physical and
economic impacts were from mortality associated with respiratory and cardiovascular diseases
attributable to long-term (i.e., chronic) exposure to methane-produced ozone, which led to over 1,400
deaths per million metric tons of methane. UNEP/CCAC results were derived from a series of global
composition-climate model (GCM) simulations in which methane mixing ratios were reduced by 50%
relative to pre-industrial levels and compared to base simulations. Consistent with previous modeling
studies [e.g., West et al., 2006], these simulations showed that background ozone levels respond linearly
to atmospheric methane changes of at least ±50% of the total anthropogenic contribution and are only
mildly sensitive to changes in other precursor emissions [UNEP/CCAC, 2021]. From these simulations,
changes in regional ozone levels per mT of global CH₄ emissions can be calculated in a manner that can
be incorporated into the social cost framework, enabling the consideration of additional ozone-health
impacts from methane to be considered in cost-benefit analyses.

This analysis is designed to apply five principles that leverage and combine key advances from previous
studies. First, to better align with the social cost framework, we assess the integrated impact of a
marginal methane emissions pulse on ozone mixing ratios through the end of the century, rather than
ozone changes associated with instantaneous emission reductions. This approach is similar to Sarofim et
al. [2017]. Second, we use changes in summertime maximum-daily 8-hour average (MDA8) ozone mixing
ratios associated with methane concentration perturbations, as derived from the recent UNEP/CCAC
simulations. The use of these gridded response maps allows us to capture spatial differences in the magnitude of ozone’s methane response, resulting from regional differences in precursor emissions and chemical production regimes. Third, we use a global instance of the Environmental Benefits Mapping and Analysis Program (BenMAP) webtool to estimate the chronic respiratory-related mortality impacts attributable to perturbed ozone mixing ratios. This is the first application of global BenMAP, which uses the most recently developed ozone exposure-mortality response function from the 2019 Global Burden of Disease (GBD) project, as well as updated projections of population and background mortality statistics. Fourth, we use the value of a statistical life (VSL) to monetize the costs associated with annual methane-ozone attributable deaths through the end of the century and integrate and discount these damages in a manner consistent with the most recent SC-GHG framework [Rennert et al., 2022a] to derive a net present damage value per mT of methane emissions. This approach is consistent with the methodology used for U.S. government calculations of the SC-CH₄ and with the health valuations used for air quality analyses by the U.S. EPA (though the assumptions necessary for global and multi-year lifetimes differ from those acceptable for local air quality analyses). Lastly, we describe the development of a new reduced form tool that uses these results to quantify ozone-related mortality changes associated with projections of perturbed methane emissions for any country and under any emission or socioeconomic scenario. This reduced form model allows for the integration of indirect methane-ozone mortality impacts into the social cost framework and provides insight into the sensitivity of this mechanism to uncertain parameters.

2. Materials and Methods

This analysis uses a multi-step approach outlined in Figure 1 to calculate the monetary value of additional respiratory-related deaths through the end of the century from ozone exposure associated with emitting a metric ton of methane in 2020. Briefly, global methane-ozone response maps (i.e., O₃ pptv / CH₄ ppbv) are used to estimate the annual change in ozone expected from a marginal pulse of methane emissions in the year 2020. The resulting ozone maps are then used as input with projected population characteristics and background mortality in a new application of the global BenMAP webtool to estimate the attributable respiratory health impacts. Annual deaths in each country are then monetized, discounted back to present day values, and aggregated over the century to produce an estimate of the global net present damages associated with ozone from a ton of methane emissions in 2020. This approach enables the estimation of ozone-related mortality benefits associated with methane emission mitigation policies and is well suited to regulatory analysis. All monetary values presented in this analysis are in 2020 U.S. dollars. The following sections provide details about each of the methodological steps and underlying data.

2.1 Tropospheric Ozone Change From a Pulse of Methane

We first estimate the annual change in global atmospheric methane mixing ratios over the 21st century, in response to a 275 million metric ton (or ~100 ppbv) methane emissions pulse in the year 2020 (Figure S1, left). For this calculation we use the atmospheric perturbation lifetime of methane of 11.8 years from the IPCC AR6 [Szopa et al., 2021] (Figure 1,1) and the methane mass to mixing ratio (Tg/ppbv) conversation factor from Prather et al. [2012] (Section S1).
To estimate the annual amount of ozone produced from this pulse, we then leverage global maps of changes in tropospheric ozone resulting from atmospheric methane changes, previously simulated as part of the UNEP/CCAC Global Methane Assessment [UNEP/CCAC, 2021] (Figure 1,2). As described in the UNEP/CCAC Assessment, multiple annual simulations were conducted using five GCMs, including the CESM2 (WACCM6) from the National Center for Atmospheric Research [Danabasoglu et al., 2020; Gettelman et al., 2019], the GFDL AM4.1 from the National Ocean and Atmospheric Administration [Dunne et al., 2020; Horowitz et al., 2020], the GISS E2.1 from NASA Goddard [Kelley et al., 2020], the MIROC-CHASER developed by the Atmosphere and Ocean Research Institute, University of Tokyo, the National Institute for Environmental Studies, the Japan Agency for Marine-Earth Science and Technology, and Nagoya University [Sekiya et al., 2018; Sudo et al., 2002; Watanabe et al., 2011], and the UKESM1 model developed by the UK Met Office and academic community [Archibald et al., 2020; Sellar et al., 2019].

In this work, we use ozone results from UNEP/CCAC simulations #1 and #2, the difference of which represents the annual ozone response to an instantaneous 50% reduction in anthropogenic methane mixing ratios, while holding all other ozone precursors constant at 2015 levels. These and other analyses presented in the UNEP/CCAC Assessment show that ozone mixing ratios respond linearly to changes in methane mixing ratios of up ± 556 ppbv, suggesting that the methane-ozone response ratios (i.e., O₃ pptv / CH₄ ppbv) derived from simulations #1 and #2 are also applicable to the range of methane perturbations tested here (~100 ppbv). Therefore, in this analysis, the methane-ozone responses derived from each of the five GCMs are formatted onto a common 0.5° × 0.5° grid and combined with annual global methane perturbations (Figure S1) to generate gridded timeseries of annual ozone changes in response to a 100 ppbv CH₄ pulse in 2020 (Figure S1, right). Figure S1 shows that the magnitude of the global ozone response varies across GCMs, however, Figure S2 also shows that the ozone response varies regionally, in part due to available ozone precursors. This motivates the need to use spatially explicit ozone-methane relationships as done here. Due to the atmospheric lifetime of methane and ozone, ozone concentrations across all regions are expected to return to their baseline values well before the end of the century (Figure S1, right). To align with recent epidemiological studies, we use the MDA8 ozone exposure metric. We also average model results over the warmest 6th months in the Northern (April – September) and Southern (October-March) Hemisphere to capture peak ozone production months. Supplemental Sections S1 and S2 provide further details on the calculation of the methane pulse and resulting maps of absolute summertime MDA8 O₃ responses.

2.2 Population and Respiratory Mortality Characteristics

To estimate projections of total population and background respiratory mortality, our analysis draws on the Resources for the Future Socioeconomic Projections (RFF-SPs) dataset. These data represent 1000 individual probabilistic projections for country-level population (Figure 1, 3) [Rennert et al., 2022b] and background all-cause mortality [Raftery and Ševčíková, 2023] (Figure 1, 4) from 2020 through 2300, stratified by age and sex. As described below, global estimated ozone-attributable mortality from a 2020 methane pulse is near negligible by the end of the century, such that we only rely on population and mortality data through the year 2100.

In this analysis, we focus on respiratory-related health endpoints as current epidemiological and toxicological research provides the strongest evidence for respiratory (vs. cardiovascular or other) health
effects resulting from long-term exposure to ozone [U.S. Environmental Protection Agency, 2020]. Baseline mortality estimates in the RFF-SP data are not differentiated by cause of death. Therefore, to capture background respiratory-related deaths (Figure 1, 5) we scale RFF-SP country-level all-cause mortality projections using data from the International Futures Project (IFP) [International Futures (IFs) modeling system]. The IFP includes projected country and age-specific estimates for both respiratory and all-cause deaths from 2000 through 2100. We take the ratio of these two as representative of the respiratory mortality fraction—by country, age, and year—projected to occur due to respiratory causes through the end of the century. We then multiply age- and country-specific all-cause mortality projections from RFF by the calculated respiratory-to-all-cause ratio projection from IFP data to derive the subset of deaths in each of the 1000 RFF-SP projections resulting from respiratory causes. Figure S3 shows the mean, 95th, and 99th percentile of the global population and derived global respiratory mortality rates from 2020-2100, with further calculation details in Section S3.

Individual projections of country-level population and derived respiratory-related mortality are then aggregated across sex and averaged across all 1000 trials for input into BenMAP. Annual country-level population data is additionally downscaled to a 0.5° x 0.5° global grid using population ‘cross-walks’, which represent the percentage of a given country’s population in each grid cell. We generate population cross-walks using the 2020 Gridded Population of the World (GPW) [Center for International Earth Science Information Network - CIESIN - Columbia University, 2018] at the 0.008° x 0.008° and 0.5° x 0.5° resolution. In contrast, mortality rates are not downscaled from country-level. Instead, BenMAP assigns a single mortality rate to all grid cells within each country, and calculates a population weighted average mortality rate for grid cells that intersect multiple countries.

2.3 Global BenMAP & Methane-Ozone Mortality

We use a new cloud-based version of U.S. EPA’s BenMAP to estimate global ozone-attributable mortality associated with a 2020 pulse of methane emissions. BenMAP was initially designed to estimate the incidence and value of health effects resulting from changes in air pollution in the United States. In addition to direct emission-air quality-health impacts, BenMAP has also been applied to climate-driven effects on air pollution and health within the U.S., such as the air quality health impacts associated with climate-driven changes in wildfire emissions [Neumann et al., 2021], southwest dust [Achakulwisut et al., 2019], pollen [Anenberg et al., 2017], heat [Morefield et al., 2018], and ozone and fine particulate matter [Fann et al., 2021] (though such climate-health related health impacts are not included in this study). More recently, the BenMAP tool was re-developed as a web application, in part to facilitate analyses with broad geographic scopes and finely resolved data inputs (Section S4). This analysis leverages these recent updates and represents the first study to estimate global air pollution health impacts using a global cloud-based version of this tool.

In this analysis, we use a log-linear health impact function within the global BenMAP framework to relate summertime MDA8 ozone exposure levels to the logarithm of respiratory deaths:

\[ y_{ct} = \text{Incidence}_{ct} \times \text{Population}_{ct} \times \left(1 - e^{-\beta \Delta O_3}\right) \]  
Eq. 1

where \( y_{ct} \) is the estimated change in annual deaths in 0.5° x 0.5° grid cell (c) and year (t). In Eq. 1, \( \beta \) is the risk coefficient associated with ozone exposure and \( \Delta O_3 \) is the change in summertime MDA8 ozone
mixing ratio. Lastly, Incidence and Population in Eq. 1 represent gridded annual estimates of the baseline background respiratory mortality rates and total population counts, respectively, for all ages 0-99 years, as described in Section 2.2.

In this analysis, we applied a chronic obstructive pulmonary disorder (COPD) relative risk coefficient of 1.06 per 10 ppb ozone exposure (95% CI: 1.03, 1.10), as estimated by the Global Burden of Disease [GBD 2019 Risk Factor Collaborators, 2020] (Figure 1, 6). This coefficient was derived from a meta-regression of five recent cohort studies in Canada, the United Kingdom, and the United States. Consistent with Malashock et al. [2022], we applied this COPD coefficient to all respiratory mortality in all countries.

Epidemiological research suggests respiratory mortality from long-term ozone exposure is not limited to COPD. This body of literature includes Turner et al. [2016], one of the largest cohort studies used in the meta-regression described above.

BenMAP is then run with two ozone air quality surfaces for each year – baseline and methane-perturbed summertime MDA8 - the difference of which represents the change in mortality attributable to ozone produced from a 2020 methane emissions pulse (Figure S1). Maps of the resulting ΔMDA8 O3 mixing ratios and attributable deaths are then aggregated to the country level for the remainder of the analysis. Due to current computational limits in the new BenMAP webtool, simulations using ozone surfaces from each GCM are run every 5 years from 2020 to 2040 and every 10 years from 2040 through the end of the century. Country-level mortality results are then interpolated between these years to derive the complete timeseries of attributable respiratory mortality counts (Figure S4).

2.4 Monetization of Methane-Ozone Mortality

This analysis uses the VSL to monetize the costs associated with chronic respiratory-related deaths each year attributable to changes in ozone from a 2020 methane emissions pulse. These do not include costs such as direct spending on health care or any environmental effects on labor productivity. Annual country-level damages associated with methane-ozone mortality estimates are calculated using the country- and year-specific VSL, shown in Eq 2., which represents the cost an individual would be willing to pay to reduce the risk of mortality.

$$VSL_{c,t} = VSL_{US,2020} \times \left( \frac{Income_{c,t}}{Income_{US,2020}} \right)^{\varepsilon}$$  \hspace{1cm} Eq. 2

Since present and future estimates of VSL are not available for each country and region, we calculate the VSL for each country (c) and year (t), by referencing to the EPA mean 2008 VSL for the U.S. [U.S. Environmental Protection Agency, 2010] (inflated to $9.3 million in 2020 dollars [U.S. Bureau of Economic Analysis, 2023]), and scaling relative to U.S. income in 2020. We also set the income elasticity (ε) to 1, following Hammitt and Robinson [2011] and Rennert et al. [2022a], such that VSL is proportional to income in each country (income = GDP per capita). Projections of country-level GDP are from the public RFF-SP dataset [Rennert et al., 2021; 2022b]. We divide country-level GDP by country-level population and use GDP per capita as the income measure. Our central estimate in this analysis uses the average population, background mortality, and GDP across all 10,000 projections. We test the sensitivity to this range of socioeconomic conditions in Section 3.
The full stream of monetized annual impacts from chronic respiratory mortality from methane-ozone are then discounted back to the year of emissions (2020) and integrated to calculate the Net Present Value (NPV). Discounting converts future impacts into present dollar equivalents, accounting for the fact that each dollar in the future is typically valued less than in the present. NPV calculations can be highly sensitive to discount rate and approach used, though less so for shorter lived gases like methane than for long-lived gases like CO₂. Therefore, we test the sensitivity to both a constant and Ramsey discounting approach. While the former applies a constant discount rate over time (effectively assuming \( n = 0 \)), the Ramsey approach in Eq. 3 allows the discount rate to scale over time with future economic growth, such that impacts are more highly valued in futures with low economic growth. The time-varying and state-specific Ramsey discount rate follows Eq. 3

\[
\text{Ramsey discounting factor}_t = \rho + \eta g_t \quad \text{Eq. 3}
\]

where \((g_t)\) is per capita economic consumption growth in each country from the year of the emissions pulse to year \(t\), \(\rho\) is the pure rate of time preference, and \(\eta\) is the elasticity of the marginal value of consumption with change in \(g_t\). We calculate the stochastic Ramsey discount factor (Section S5) and apply the resulting time-varying rate in Eq. 4, such that the NPV in each country is

\[
\text{NPV} = \sum_{t=2010}^{2100} \frac{\text{Annual damages}_t}{(1+\text{Ramsey discount factor}_t)^{t-2010}} \quad \text{Eq. 4}
\]

This approach has been used in recent NPV analyses of climate health related damages [Hartin et al., 2023] and is generally consistent with the social cost of carbon framework, recently applied in Rennert et al. [2022a]. However, for consistency with country-specific VSLs, this analysis uses discount factors based on country-level consumption growth rather than the world average, which results in a more conservative NPV estimate (Section S5). Our central estimate focuses on results discounted using time-varying Ramsey discount rates, calibrated to a near-term discount rate of 2.0%. Additional details are described in Section S5. All results in this analysis are presented in units of 2020 U.S. dollars, converted from 2011 values (RFF-SP dollar units) using Annual GDP Implicit Price Deflators [U.S. Bureau of Economic Analysis, 2023].

2.5 Reduced Form Model

To further assess the sensitivity of the monetized damages to alternative socioeconomic projections and emission scenarios, we supplement the BenMAP analysis with a custom reduced form tool. The reduced form model is an R-based tool that adjusts the BenMAP generated attributable mortality counts to produce new estimates of annual country-level methane-ozone attributable respiratory-related deaths from a pulse of methane emissions, following Eq 5:

\[
\text{Mortality}_{c,t,p} = \text{Mortality}_{c,t,b} \times \left( \frac{\text{Incidence}_{c,t,p}}{\text{Incidence}_{c,t,b}} \right) \times \left( \frac{\text{Population}_{c,t,p}}{\text{Population}_{c,t,b}} \right) \times \frac{\text{O}_3 \ \text{Response}_{c,t,p} \times \text{CH}_4 \ \text{Pulse}_{t,p}}{\text{O}_3 \ \text{Response}_{c,t,b} \times \text{CH}_4 \ \text{Pulse}_{t,b}} \quad \text{(Eq. 5)}
\]

where the updated mortality estimates for each country \((c)\) and year \((t)\) and for each new projected scenario \((p)\) are equal to the original annual mortality estimates from BenMAP \((b)\), scaled by the ratio of the background respiratory mortality incidence, total population, and summertime ΔMDA8 O₃ in the new projected scenario relative to those in the original BenMAP simulations. In Eq. 5, the ratio of summertime MDA8 O₃ levels is calculated as the average O₃ response to methane \((\text{O}_3 \ \text{pptv/CH}_4 \ \text{ppbv})\)
across each country and year, multiplied by annual ΔCH₄ concentrations from an emissions pulse in a
given year. The O₃ response in the original BenMAP simulations are assumed constant over time and the
annual perturbed CH₄ concentrations in any new scenario are calculated using the pulse size and
atmospheric lifetime of CH₄, as discussed in Section 2.1 (Figure S1).

While the formulation in Eq. 5 assumes linear relationships at the country level between changes in
perturbed ozone, population characteristics, and attributable deaths, the efficiency of tropospheric O₃
production from atmospheric methane (i.e., O₃ response) is sensitive to changes in O₃ precursors, such
as nitrogen oxides (NOₓ = NO + NO₂). Therefore, the logarithmic relationship in Eq. 6 can be used to
relate changes in NOₓ emissions to changes in the O₃-methane response in each country. We leverage
the relationships derived as part of the UNEP/CCAC Global Methane Assessment, from two additional
sets of simulations that assessed the change in O₃ response with methane at varying NOₓ emission levels
[UNEP/CCAC, 2021].

\[
\frac{\Delta MDA8 O₃ (ppbv)}{CH₄ (ppbv)} = \frac{1000 \times (slope \times \ln(NOₓ)+intercept)}{556 \text{ ppbv}}
\] (Eq. 6)

The resulting annual country level mortality estimates from the reduced form tool (under any custom
scenario) can be monetized, discounted, and aggregated using the methods described in Section 2.4.
Sensitivities of annual monetized and discounted NPVs to changes in socioeconomic and NOₓ emission
projections, as predicted by the reduced form tool, are presented in Section 3.

3. Results & Discussion

3.1 Physical Impacts

Globally by the end of the century, an estimated total of 210,000 (95% Confidence Interval: 90,000-
330,000) respiratory related deaths would be attributable to tropospheric ozone produced from a 275
MMT pulse of methane emissions in 2020. Figure 2a illustrates that, in the absence of cessation lags,
annual mortality counts peak in the same year as the initial emissions pulse, which also coincides with
the timing of the largest perturbations in methane and ozone concentrations (Figure S1). Annual
physical impacts are calculated directly by the global BenMAP webtool, using average population and
respiratory mortality rate projections as described in Section 2 and the ΔMDA8 summertime O₃ mixing
ratios per change in methane mixing ratio from the mean of the five GCMs (MMM). Uncertainty in the
GBD ozone concentration response function (CRF) underlying BenMAP (β 95% CI: 1.03-1.10 per 10 ppbv
O₃) is shown by the 95th percent confidence interval in Figure 2a. Annual estimates are also sensitive to
differences in the methane-ozone response in each GCM (Figures S4 & S5) and range from a total of
140,000 deaths through the end of the century predicted by the MIROC model, up to 320,000 total
attributable deaths predicted by HadGEM (95% CI: -43% to +56% for both), given average population
characteristics. A discussion of these and additional uncertainties associated with socioeconomic
projections, precursor emissions, and valuation are discussed in Section 3.3.

Figure 2b additionally illustrates that CH₄-O₃ attributable respiratory-related deaths are not distributed
evenly across countries and regions. As BenMAP applies the same ozone concentration response
function to all regions, heterogeneity in mortality counts across countries is driven by a combination of
differences in country-level population, background respiratory mortality rates (Eq. 1), as well as
differences in the modeled ozone response to methane change (Figure S2). While absolute population is
the main driver of these differences (Figure S6a), by normalizing mortality counts per capita in Figure 2b,
the remaining spatial differences illustrate that additional differences in regional background respiratory
mortality rates and ozone response to methane are also important factors. For example, while highly
populated countries in the South Asia ‘GBD Super Region’ (Table S1) are estimated to collectively have
the largest total attributable mortality counts (40% of global total), panels b-c in Figure S6 also show
that countries in this region have higher background mortality rates and more efficient methane-ozone
production (≈4.6 pptV O_3/ppbv CH_4) relative to the population-weighted global modeled average (4.1
pptV O_3/ppbv CH_4) (e.g., Figure S2). Likewise, relatively lower deaths per capita in central Africa are in
part due to relatively lower respiratory mortality rates and less efficient methane-ozone production
(Figure 6). While West et al. [2006] previously showed all-cause per capita methane-ozone impacts
were greatest in countries within the Africa region, that study similarly found that per capita
cardiovascular and respiratory-related mortality impacts were relatively greater throughout Europe,
which is generally consistent with our results. The Global Methane Assessment likewise reported similar
spatial patterns to those shown here other than for Sudan [UNEP/CCAC, 2021].

Lastly, due to the linear relationship between changes in atmospheric methane and ozone, we scale
total integrated deaths from our original pulse down to 760 (95% CI: 330-1200) total deaths per million
metric tons (MMT) of CH_4. The deaths/MMT results from this work are slightly larger, but comparable to
previous similar studies. For example, the UNEP/CCAC Global Assessment estimated 740 (95% CI: 460-990) respiratory-related attributable deaths per MMT CH_4, as well as an additional 690 (95% CI: 210-1120) attributable deaths from cardiovascular diseases [UNEP/CCAC, 2021]. Though these values are
derived from the same GCM simulations used in this work, respiratory estimates slightly vary from those
presented in this study due to differences in the β, minimum exposure limit (Section S4), and
assumptions of constant 2015 populations and mortality rates relative to dynamic population
projections used here. In contrast, Sarofim et al. [2017] estimated 239-591 deaths/MMT, which is
smaller than estimates here in part due to the spatially homogenous methane perturbation assumption
used in that study. Assuming a homogeneous, globally averaged methane-ozone response across all grid
cells in our study also results in lower mortality estimates, which fall within the Sarofim et al. [2017]
range. Lastly, all-cause mortality estimates from methane-ozone derived from West et al. [2006] are
close to 300 deaths/MMT, which may be lower than our estimates due to differences in modeling
approach, simulated methane ozone response, β, and population and mortality characteristics. We
discuss sensitivities to each of these parameters in our study below.

3.2 Economic Damages

As described in Section 2, annual streams of attributable deaths in each country are monetized,
discounted back to present day values, and integrated to derive a NPV of the total economic damages
associated with ozone-attributable respiratory-related deaths per mT of methane emissions. Due to the
linear relationship between atmospheric methane and ozone changes, we linearly scale the total
integrated discounted damages from our original 275 MMT (or 100 ppbv) pulse down to units of dollars
per metric ton (mT) of CH_4.
Globally, the central NPV derived from the MMM and using a 2% Ramsey discount rate is $1700/mT CH₄ (95% CI: $710-$2600/mT CH₄). The 95% confidence interval is associated with the upper and lower bounds of the ozone exposure response function in the global BenMAP webtool. Mean NPV results are most sensitive to these BenMAP uncertainties. These and additional sensitivities are discussed in the following section. Similar to the regional trends in physical impacts, the total economic damages related to methane-ozone mortality are not evenly distributed across world regions (Figure 2c). As anticipated, large NPV values are estimated across regions that also have large attributable mortality counts, however, net present damages are estimated to be largest in the ‘High Income’ region ($610/mT CH₄; 95% CI: $260-$960/mT CH₄), in part because of regional differences in projected income. These large values in the high-income region are driven by large NPV’s in the U.S., Japan, and throughout western Europe (Table S1). The region with the second highest aggregate NPV is the Southeast Asia, East Asia, and Oceania region ($550/mT CH₄; 95% CI: $230-$860/mT CH₄), driven by high values in China, followed by the South Asia ($290/mT CH₄; 95% CI: $120-860/mT CH₄) and North Africa and Middle East regions ($90/mT CH₄; 95% CI: $40-$140/mT CH₄). NPV’s for the top 20 countries are shown in Table S1.

Given sensitivities to differences in assumptions regarding discount rates, concentration response functions for mortality, VSLs, and other factors, results from previous studies can be challenging to compare with more recent numbers, particularly for older studies such as West et al. [2006]. Even for newer studies, there are many differences in assumptions that drive the differences between estimated valuations. For example, [UNEP/CCAC, 2021] estimated a value of (2020) $2580/mT CH₄ including cardiovascular deaths with a value of $1335/mT CH₄ for respiratory deaths only, as in this study, similar to the value reported here. Their calculation used a constant discount rate of 3%, and didn’t include future increases in population, which may account for the slightly lower valuation. Sarofim et al. [2017] presented a range of (2020) $900-$2100/mT CH₄ within the range of results here, despite projecting fewer deaths and using a higher discount rate: however, the elasticity of VSL to GDP/capita used in Sarofim et al. [2017] was 0.4, which both Sarofim et al. [2017] and [UNEP/CCAC, 2021] have shown leads to a doubling of the damage estimate relative to an elasticity of 1. Using a consistent monetization and discounting approach as the updated social cost of carbon framework, our monetized impacts of ozone per mT of CH₄ are larger than the current SC-CH₄ estimates of $1500/mT (3% CDR) used by the U.S. government [Interagency Working Group on Social Cost of Greenhouse Gases (IWG), 2021], as well as the recently updated estimates of $1600/mT CH₄ (2% Ramsey) [EPA, 2022], both of which are only based on climate-related damages.

3.3 Uncertainties and Sensitivities

Consistent with previous approaches to estimating the social cost of greenhouse gases, there are many sources of uncertainty in estimating the physical and economic impacts from ozone produced from a ton of methane emissions. Major sources of uncertainty include but are not limited to: climate model representation of atmospheric conditions that drive ozone production from methane, the sensitivity of ozone production chemistry to precursor emissions, projections of country-level GDP, population counts and total all-cause and cause-specific mortality rates through the end of the century, changes in the respiratory-related health risk associated with changes ozone exposure, as well as the discount approach and rate used to monetize the full stream of annual damages. Figure 3 summarizes the
sensitivity of the global NPV to these major sources of uncertainty which are discussed in order of decreasing sensitivity below.

Concentration Response Function

The global NPV from respiratory-related deaths attributable to methane-produced ozone is sensitive to uncertainties in the ozone concentration response function ($\beta$) implemented in BenMAP. As shown in Figure 2a, the 95% confidence interval of $\beta$ values from the GBD (1.03-1.10/10 ppbv O$_3$ [GBD 2019 Risk Factor Collaborators, 2020]) results in a range of total integrated mortality counts of 90,000-330,000 (mean: 210,000 deaths), which corresponds to a change in global NPV of -57% to +56% (or $-710-$2600/mT CH$_4$) (Figure 3). Additional related uncertainty not considered here also arises from the application of the COPD hazard ratio to respiratory mortality (as described in Section 2.3), provided the COPD ratio includes more diseases, but is the best available at the global scale.

Socioeconomics

Due to the computational requirements to run the global BenMAP webtool for each simulation year, climate model air quality surface, and future population and mortality projection, we alternatively develop a computationally efficient reduced form tool that can facilitate SC-CH$_4$ calculations and can be run with any of the 10,000 probabilistic socioeconomic projections from the RFF-SPs [Raftery and Ševčíková, 2023; Rennert et al., 2021]. Additional runs for specific projections with the BenMAP tool show that the reduced form tool can reproduce BenMAP respiratory-related deaths to within 0.5% (Section S6). We run the tool for all 10,000 future scenarios here to test the sensitivity of the mean NPV to the range of future socioeconomic (total population, mortality rates, GDP) projections. Figure 3 shows that across all future RFF-SP scenarios of country-level socioeconomic data, the 95% confidence interval of the global NPV with a 2% Ramsey discount factor is -18% to +19% (or $1400-$2000/mT CH$_4$). As an additional evaluation of the reduced form tool, the mean NPV resulting from all 10,000 individual trajectories is within 1.5% of the NPV derived from the mean BenMAP run, which used a single projection of population, mortality, and GDP, calculated as the average of all 10,000 RFF-SP scenarios.

Ozone Production Chemistry (Global Climate Model & Precursor Emissions)

The atmospheric production of tropospheric ozone requires the presence of NO$_x$, volatile organic compounds (VOC) or carbon monoxide (CO), and sunlight. The efficiency of this non-linear relationship depends on the relative abundance of precursors, as well as factors that affect photochemical rates (i.e., temperature, sunlight, surface reflectance, etc.), such that O$_3$ production may become more or less sensitive to changes in background methane levels depending on these conditions. As described in the UNEP/CCAC Global Methane Assessment, global simulations of tropospheric ozone changes in response to methane reductions were run with five GCMs. As each model incorporates different parameterizations of the physical and chemical conditions driving tropospheric ozone production, each model predicts a different level of absolute ozone change in response to global methane reductions (Figure S1), as well as a different spatial pattern of this response (Figure S2).

In this work, maps of summertime MDA8 O$_3$ resulting from a 2020 CH$_4$ emissions pulse are calculated using 0.5°×0.5° gridded O$_3$/CH$_4$ response relationships derived from UNEP/CCAC simulations (assuming a constant response relationship over time). Therefore, to test the sensitivity of the economic impacts
from the choice of GCM, we run the BenMAP webtool with \( O_3 \) maps calculated from the ozone response in each of the five GCMs, taking our central value from the multi-model mean (MMM). As shown in Figure 3, the five GCMs result in a spread of global NPV (with 2% Ramsey discount factor) of -30% to +45% (or $1200-$2400/mT CH\(_4\)) relative to the MMM.

In addition to GCM chemistry and parameterizations, the chemical response of \( O_3 \) production to changes in background methane levels (e.g., pptv \( O_3 \)/ ppbv CH\(_4\)) is also sensitive to the relative abundance of NO\(_x\) and VOC+CO precursor emissions. As shown in the UNEP/CCAC Global Methane Assessment, methane emission changes will have a smaller impact on \( \Delta \text{MDA} \) \( O_3 \) as regional NO\(_x\) emissions are reduced and ozone photochemistry becomes more NO\(_x\)-limited (i.e., VOC saturated). In contrast, methane will have a larger impact on \( \Delta \text{MDA} \) \( O_3 \) as NO\(_x\) emissions increase, and ozone photochemistry becomes more VOC-limited. Despite the complex non-linear nature of this chemistry, an additional set of UNEP/CCAC simulations using varying NO\(_x\) emissions showed that the ozone response to changes in methane generally follows a log-linear relationship with changes in absolute NO\(_x\) emissions (Eq. 6), but that the slope and intercept of this relationship varies by country. The ozone-methane sensitivity was also found to be much weaker for changes in other VOC emissions, such that no relationship was derived. Previous simulations by West et al. [2006] also found a low sensitivity of the ozone-methane response to changes in either NO\(_x\) and VOC precursor emissions. Here we test the sensitivity to changes in NO\(_x\) emissions by parameterizing the methane-ozone response relationship in the reduced form tool using the NOx-O\(_3\)/CH\(_4\) relationship for each country, derived from the UNEP/CCAC simulation results (Eq. 6). Simulating a 50% change in NO\(_x\) emissions in each country relative to original model levels (from UNEP/CCAC simulations) results in a NPV change (MMM, 2% Ramsey discount factor) of -17% to +10% (or $1400-$1800/mT CH\(_4\)). Additional sensitivity to changes in NO\(_x\) emissions over time were not tested here but could be implemented in the reduced form tool (Section S6) and are expected to have a relatively smaller impact on discounted future damages. These combined results suggest that damages associated with mortality attributable to methane-produced ozone are more highly sensitive to choice in GCM rather than the impacts of NO\(_x\) emissions on photochemical methane-ozone production efficiency.

Additional uncertainties include the sensitivity to model resolution, as well as the change in NO\(_x\)/VOC sensitivity in a region over time, and the contribution of methane to localized ozone production (e.g., <1km scale). Therefore, while this analysis is generally consistent with the global SC-GHG framework, the approach used here is less relevant for resolving highly localized air quality benefits.

**Discounting**

Consistent with recent analyses of the social cost of greenhouse gases [Rennert et al., 2022a], the NPV's in this analysis are also modestly sensitive to the discount approach and factor used (constant discount factor vs. time-varying Ramsey approach). The central value in this analysis uses the 2.0% Ramsey discount factor approach but ranges from $1400/mT CH\(_4\) with a 3.0% Ramsey discount factor up to $1900/mT CH\(_4\) with a 2% constant discount factor. Discount factors are calculated at the country-level. Aggregated regional NPV's across all discount factors tested here are shown in Figure S7.

**Additional Uncertainties & Limitations**

Additional uncertainties that are not included in Figure 3 include the possible delay between initial ozone exposure and the year when death is estimated to occur (cessation lags), the minimum exposure
level under which there is no additional risk from ozone exposure (TMREL), the calculation of the
country-specific VSL based on projections of future income, additional short term health effects,
mortality that might occur in the winter months, or the consideration of damages from additional health
endpoints, such as increased hospitalizations or asthma cases. The global total mortality counts from the
MMM are only minorly sensitive to the TMREL (-3%, Section S4), and implementation of cessation lags
only reduce the global NPV by 2.5% (Section S5) relative to the MMM. There are also uncertainties
associated with the epidemiologic studies underlying the estimates of ozone exposure risk used here.
Some of these include using a pooled hazard ratio from a limited number of studies in developed
countries and applying that to the countries in the developing world, as well as using historical
associations between exposure and adverse effects to quantify these risks in the distant future. These
and additional sensitivities are not tested here but could, in part, be explored using a range of input
parameters in the reduced form tool (Section S6).

One additional potential benefit of the reduced form model is the ability to assess methane
perturbation results from external climate models such as FalR [Leach et al., 2021]. In this paper, a
constant methane lifetime of 11.8 years was used, but future methane lifetime is a function of future
emissions of VOCs, NOx, and methane itself, as well as of changes in global temperature and other
factors. A note of caution, however, is that the factors impacting the methane lifetime would also be
expected to change the ozone production relationship, and besides the NOx sensitivity analysis discussed
above, the reduced form model doesn’t have any ability to account for the effects of these other
changes.

5. Conclusions

This analysis combines the SC-CH4-relevant best practices of earlier papers (including the use of future
population characteristics as in Sarofim et al. [2017], heterogenous ozone response as in [UNEP/CCAC,
2021], and socioeconomic and population projections from Rennert et al. [2021]), in order to estimate
an SC-CH4 consistent set of damages resulting from ozone produced from CH4 emissions. The global NPV
magnitude ($1700/mT CH4) is comparable in size to the most recent climate-based SC-CH4 estimates.
The NPV is most sensitive to uncertainties in the health impacts of ozone exposure, parameterized
ozone production chemistry in GCMs, and assumptions in future socioeconomic conditions. The
additional development of a reduced form model, based on detailed underlying climate-chemistry and
health impact models, allows this work to be coupled to alternative assumptions about future
populations, mortality rates, precursor emissions, pulse year, and monetization assumptions (such as
the base VSL, the elasticity of VSL with income, and the discount rate). This could enable integration
with SC-CH4 estimation frameworks such as the GIVE model [Rennert et al., 2022a]. These advances are
potentially an important step to including these effects in future cost-benefit analyses.

Acknowledgement

We thank Hana Ševčíková and the Resources for the Future team for providing age-specific population
and mortality projections. We thank the authors of the UNEP/CCAC Global Methane Assessment for
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Notes

The views expressed in this manuscript are those of the authors and do not necessarily represent the views or policies of the U.S. Environmental Protection Agency.

Open Research

Global BenMAP model instance and instructions are available here https://zenodo.org/record/7930887. The reduced form model code, inputs, results, and analysis and figure scripts for this paper are available at: https://github.com/USEPA/MOMM-RFT. Data used in this analysis from the UNEP/CCAC Global Methane Assessment are also available at: https://github.com/USEPA/MOMM-RFT.

Author Contributions

The manuscript was written by EM, MS, WR, and MJ, with contributions from all co-authors. Data from the UNEP/CCAC Global Methane Assessment were provided and processed by KS and BH. BenMAP simulations were run by JA & MC. Population & mortality data were processed by MJ. EM & MJ conducted the remaining analysis and developed the reduced form tool. MS and NF conceived of the analysis. Figure 1 was created by SB.

Reference List


manuscript drafted for AGU's Earth's Future


International Futures (IFs) modeling system Version 7.88, Pardee Center for International Futures, Josef Korbel School of International Studies, University of Denver, Denver, CO, https://korbel.du.edu/pardee/international-futures-platform/download-ifs.


U.S. Bureau of Economic Analysis (2023), *Table 1.1.9. Implicit Price Deflators for Gross Domestic Product*, [https://apps.bea.gov/iTable/?reqid=19&step=3&isuri=1&select_all_years=0&nipa_table_list=13&series=a&first_year=2006&last_year=2020&scale=-99&categories=survey&thetable=] [last accessed: January 24, 2023].


Additional References from the SI


Figure Captions

Figure 1. Schematic of analysis workflow. Logos for individual groups and initiatives are used for illustrative purposes only and do not represent endorsement.

Figure 2. Physical and economic impacts of ozone produced from a 2020 275 MMT emission pulse of methane. A) timeseries of annual global respiratory-related deaths attributable to O3 exposure (with CRF uncertainty) and methane (insert), b) respiratory-related deaths per capita attributable to ozone in 2020, by country, c) net-present value of methane-ozone attributable respiratory related deaths (with CRF uncertainty), globally and by GBD Super Region.

Figure 3. Sensitivity of the mean global NPV to uncertain analysis parameters. The top four bars represent the ranges associated with the 95% confidence interval of the BenMAP concentration response function (CRF) (red) and RFF-SP socioeconomic projections (orange). The remaining bars represent changes in the mean value associated with ±50% changes in NOx emissions (green), differences across five GCMs (blue), and five discounting rates and approaches (Ramsey & constant discount rates) (purple). Socioeconomic and NOx sensitivity results were derived from runs with the reduced form tool, while remaining sensitivities were derived from the central BenMAP run.
Figure 2.
Figure 3.
Supplement to:

The Social Cost of Ozone-Related Mortality Impacts from Methane Emissions

Erin E. McDuffie\(^1\), Marcus C. Sarofim\(^1\), William Raich\(^2\), Melanie Jackson\(^2\), Henry Roman\(^2\), Karl Seltzer\(^3\), Barron Henderson\(^3\), Drew T. Shindell\(^4\), Mei Collins\(^2\), Jim Anderton\(^2\), Sarah Barr\(^1\), Neal Fann\(^5\)

\(^1\)Office of Atmospheric Protection, Climate Change Division, U.S. Environmental Protection Agency, Washington, DC, USA

\(^2\)Industrial Economics, Incorporated, Cambridge, MA, USA

\(^3\)Office of Air Quality Planning and Standards, Air Quality Assessment Division, U.S. Environmental Protection Agency, Research Triangle Park, NC, USA

\(^4\)Nicholas School of the Environment, Duke University, Durham, NC, USA

\(^5\)Office of Air Quality Planning and Standards, Health and Environmental Impacts Division, U.S. Environmental Protection Agency, Research Triangle Park, NC, USA

Contents

1. Atmospheric Methane Changes
2. Calculated Tropospheric Ozone Changes
3. Population & Mortality Characteristics
4. BenMAP Mortality Estimates
5. Monetization
6. Methane-Ozone Mortality Model – Reduced Form Tool
Section S1. Atmospheric Methane Changes

Figure S1. Timeseries of perturbed annual average atmospheric methane (left) and Δ summertime maximum daily 8-hour average (MDA8) ozone mixing ratios (right), in response to a 275 MMT pulse of methane in the year 2020. ΔMDA8 ozone results are shown for each model. The baseline CH₄ mixing ratio (1834 ppbv) is shown by the left dashed line.

The first step in the analysis workflow shown in Figure 1 is to estimate the perturbations in atmospheric methane concentrations through the end of the century, associated with a pulse of methane emissions in the year 2020. We chose a pulse size of 275 million metric tons (MMT) of CH₄, which corresponds to a mixing ratio of ~100 ppbv following the 2.75 Tg/ppbv CH₄ conversion factor, from Prather et al. [2012], used in the 5th Assessment Report of the IPCC.

Reproduced from Prather et al. [2012] Supplemental Text S1:

\[
2.75 \, \text{Tg CH}_4 \, \text{ppbv} = 0.1764 \, \frac{\text{Tmoles air}}{\text{ppbv}} \times 16 \times \frac{\text{Tg CH}_4}{\text{Tmoles CH}_4} \times 0.973 \, \frac{\text{Tmoles CH}_4}{\text{Tmoles air}} \quad (\text{Eq. S1})
\]

As methane will exponentially decay in the atmosphere (unless resupplied), we use the perturbation lifetime of methane (\(\tau = 11.8\) years) from IPCC AR6 [Szopa et al., 2021] in Eq. S2 to derive the timeseries of perturbed methane mixing ratios shown in Figure S1. In Eq. S2, the initial pulse of methane
is 100 ppbv and the baseline is 1834 ppbv, from the UNEP/CCAC Global Methane Assessment simulations [UNEP/CCAC, 2021].

\[
\text{Perturbed } [\text{CH}_4]_t = \text{Pulse } [\text{CH}_4]_{t=0} e^{-\Delta t/\tau} + \text{Baseline } [\text{CH}_4] \quad (\text{Eq. S2})
\]

**Section S2. Calculated Tropospheric Ozone Changes**

As described in the main text, the timeseries of perturbed methane mixing ratios associated with a pulse of emissions in 2020 is combined with methane-ozone response maps (i.e., O₃ pptv/CH₄ ppbv) from the UNEP/CCAC Global Methane Assessment to calculate spatially explicit maps of ozone concentrations over time, in response to the initial 2020 CH₄ pulse. As discussed in the UNEP/CCAC Global Methane Assessment Report, the ozone response per ppbv of methane change is linear across the range of methane changes analyzed in the report (± 556 ppbv), which is larger than the 100 ppbv pulse size tested here. While linear, the magnitude of the ozone response to methane does vary regionally, as discussed below. We use the UNEP/CCAC O₃ response maps from each of the 5 GCMs used in the UNEP/CCAC Assessment, as well as resulting ozone concentrations calculated from the mean across all models (MMM). The gridded methane-ozone response relationships used to calculate these maps are derived from the changes in O₃ and CH₄ between simulations #1 and #2 from the UNEP/CCAC Assessment.

The calculated (unweighted) ozone responses to a 100 ppbv methane pulse for each model in the year 2020 are provided in Figure S2. The global population-weighted responses for each model are as follows (in pptv O₃ / 100 ppbv CH₄): HadGEM: 659, CESM2: 518, GFDL: 381, GISS: 364, MIROC 296, MMM: 480. These population-weighted responses for each model are slightly larger than the corresponding global average given that sunlight, water vapor, and halogens efficiently destroy ozone over the ocean [Read et al., 2008] and net production tends to increase over populated regions with abundant precursor emissions.

In addition to global average results, Figure S2 also shows that the O₃ response to methane is spatially heterogeneous. While the spatial patterns are slightly different across each model, each model predicts that the largest anticipated changes are primarily centered over the Middle East and central, south, and east Asia. The patterns and magnitudes of calculated ozone changes in Figure S2 in response to methane are also consistent with the UNEP/CCAC Assessment, such that the UKESM model has the largest average O₃ response to changes in methane emissions (global average change: 383 pptv/100 ppbv CH₄), while the MIROC-CHASER has the smallest (global average change: 274 pptv/100 ppbv CH₄).
**Figure S2.** Calculated changes in summertime MDA8 ozone mixing ratios (in units of pptv) in 2020 for each model and the calculated multi-model mean (MMM), in response to a 100 ppbv methane emissions pulse in the same year. The global average change (no weighting) is provided in each panel.

Figures S1 shows that due to the lifetime of CH$_4$ and O$_3$, the global atmospheric abundance of both CH$_4$ and O$_3$ return to their initial 2020 levels well before the end of the century, such that integrating the impacts between 2020 and 2100 will capture the majority of climate damages resulting from this methane-ozone-health mechanism.

**Section S3. Population & Mortality Characteristics**

As described in the main text, projections of total population and background respiratory mortality rates are calculated for each country using a combination of data from the Resources for the Future-Socioeconomic Projections dataset (RFF-SP) [Rennert et al., 2022b] and the International Futures Project (IFP) [International Futures (IFs) modeling system]. The public RFF-SP database contains 10,000 probabilistic projections of greenhouse gas emissions, total population, and gross-domestic product (GDP) for 184 countries from 2020-2300. As described in Rennert et al. [2021], total population data in the RFF-SP dataset are drawn from 1000 individual population projections from Raftery and Ševčíková [2023], which in part rely on projections of country-specific, age- and sex-stratified background mortality rates. We obtained this population and all-cause mortality dataset via personal communication from H. Ševčíková, which contains 1000 individual projections of population and mortality rates for 19 age bins (every five years from ages 0-4 through 90+) and 201 countries.

To derive respiratory-specific mortality rates, the 1000 individual country-specific all-cause rates are scaled by the ratio of projected respiratory-to-all-cause mortality – by age and country– from the International Futures Project [International Futures (IFs) modeling system]. The IFP dataset contains respiratory and all-cause mortality rates from 2000-2100, by sex, for 22 age bins and 186 countries. These age bins were merged into the same 19 bins as the RFF-SP data and the sex-stratified rates were used to find the population weighted average rates. For the 15 countries in the RFF data that are not
included in the IFP dataset (primarily small islands nations), respiratory-all-cause mortality ratios were assigned to those in the nearest geographical country. Figure S3 shows the resulting global projections of total population and calculated global respiratory mortality rate for the 1000 projections. Central results presented throughout the main text are derived using the average of these data (Figure S3, red line). Note that consistent with similar types of air quality impact studies, this study design does not account for the effects of respiratory deaths on the projected populations as the population projections are developed separately from the ozone-health modeling conducted here.

![Global Population & Mortality Rate Projections](image)

**Figure S3.** Projections of global population and respiratory mortality rates. Mean, 95th, and 99th percent confidence intervals are shown in red, gray, and light gray respectively. Global population data are aggregated across country, age, and sex. Global respiratory mortality rates are calculated as the aggregate of country-level respiratory mortality counts (\(\sum\)country mortality rate \times country population), divided by the global total population (aggregated across country, age, and sex).

Additional socioeconomic sensitivity tests presented in Section 3 of the main text are conducted with the full set of 10,000 public RFF-SP population and GDP data, paired with the corresponding background mortality projections using a crosswalk between the public RFF-SP trial number and the corresponding draw number from the 1000 population/mortality projections.

**Section S4. BenMAP Mortality Estimates**

As described in the main text, the new BenMAP cloud-based webtool was expanded in this work to cover the global region and leverage cloud computing resources. The BenMAP webtool used inputs of re-gridded 0.5° x 0.5° global maps of MDA8 O₃ (with and without 2020 CH₄ pulse perturbations) calculated for each of the 5 GCMs, as well as downscaled global grids of total population and mortality rates. BenMAP then aggregates population and mortality data across the 0-99 age group and calculates the respiratory-mortality attributable to the change in ozone exposure for each country following Eq. 1 in the main text. The code and documentation for an archived version of the BenMAP application is here: [https://zenodo.org/record/7930887](https://zenodo.org/record/7930887). Additional code used to run the global BenMAP webtool are available on the BenMAP github repository: [https://github.com/BenMAPCE/BenCloudApp/tree/develop-global-ozone](https://github.com/BenMAPCE/BenCloudApp/tree/develop-global-ozone); [https://github.com/BenMAPCE/BenCloudServer/tree/develop-global-ozone](https://github.com/BenMAPCE/BenCloudServer/tree/develop-global-ozone)
As this analysis is not a standard ‘burden’ analysis and is instead focused on estimating increases in mortality attributable to ozone from an additional pulse of methane emissions, we do not implement a theoretical minimum risk exposure level (TMREL). The 2019 GBD recently suggested a uniform distribution of the long-term ozone TMREL between 29.1 and 35.7 ppbv, based on the underlying studies [GBD 2019 Risk Factor Collaborators, 2020]. Implementing the median TMREL from this distribution (32.4 ppbv), following the approach of Malashock et al. [2022], would reduce the integrated total number of global ozone attributable respiratory-related deaths in this analysis by 3.1% (or 6,500 deaths).

**Figure S4.** Timeseries of annual global methane-ozone attributable respiratory deaths, by GCM

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<th>Model</th>
<th>CESM2</th>
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</table>

**Figure S5.** Maps of total integrated methane-ozone respiratory related attributable deaths, by country and model.
Figure S6. Snapshot of country differences in the year 2020 in a) population, b) background respiratory mortality rates per 100K, and c) modeled average ozone response to methane changes. The color scale ranges from the minimum to maximum value in each panel, by country.
**Section S5. Monetization**

The damages associated with increased respiratory-related deaths attributable to ozone formed from a marginal methane emissions pulse are monetized using country-specific VSL values. As described in Section S3, the full RFF population & mortality dataset from *Raftery and Ševčíková* [2023], contain data for 201 countries (Table S1), while the public version of the full 10,000 probabilistic emission, population, and GDP draws only contain data for 184 countries. For those 17 countries in the public RFF-SP dataset that were not included in the underlying population dataset (primarily small island nations), VSL values are assigned to those calculated at the broader region level (Table S1).

Annual mortality counts for each country and GCM through the end of the century are then discounted back to 2020 U.S. dollars using multiple discounting approaches. The first uses constant discount factors of 2.0% and 3.0%. The second approach follows recent literature and updated OMB guidelines to apply a time-varying Ramsey discounting approach (Eq. 3), calibrated to near-term discount rates of 1.5%, 2.0% (presented in the main text), 2.5%, and 3.0% [Rennert et al., 2022a]. For these rates, the values for \( \rho = 0.01\%, 0.2\%, 0.5\%, 0.8\% \) and \( \eta = 1.02, 1.24, 1.42, 1.57 \), respectively.

Consistent with Rennert et al. [2022a], we calculate the stochastic discount rate to discount future marginal mortality-related damages from the methane-ozone-health mechanism. The stochastic discount factor can be written in terms of relative consumption levels for each year \( t \) and country \( c \), following Eq. S3.

\[
\text{Stochastic Ramsey Discount Factor}_{c,t} = \frac{1}{(1+\rho)^{t-2020}} \left( \frac{c_t}{c_{2020}} \right)^{-\eta} \quad (\text{Eq. S3})
\]

Where \( c_t \) in this work is the country level per capita consumption in year \( t \) and \( \eta \) is transformed by \( \eta = \exp(\eta) - 1 \). In this analysis, we use country specific VSL, growth, damages, and discounting, which effectively produces an equity weighted result. This differs from the SC-CH₄ calculation of Ramsey discount rates, which uses country-specific VSL, but takes \( c_t \) as world average consumption rate [Rennert et al., 2022a]. Applying a global average consumption rate to discount the methane-ozone damages in this analysis increases the global NPV by \(~7\%\). The stochastic discount factors for each year and country are then multiplied by the marginal damages and aggregated over time into a single present value.

\[
\text{NPV}_{c,t} = \sum_{t=2020}^{2100} \text{SDF}_{c,t} \times \text{Marginal Damages}_{c,t} \quad (\text{Eq. S4})
\]
Figure S7. Net Present Value (NPV) per ton of methane emitted in 2020, as a function of region and discount factor.

Table S1. Country names and regions included in this analysis. Country names and groups are consistent with those in the Global Burden of Disease project. The relative ranking and NPVs (2020$\text{}/\text{mT } \text{CH}_4; \%\text{ Ramsey discount rate}) are listed for the largest 20 countries.

<table>
<thead>
<tr>
<th>Central Europe, Eastern Europe, Central Asia</th>
<th>Russian Federation (12; $20/mT)</th>
<th>France (11; $20/mT)</th>
<th>South Korea (14; $20/mT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albania</td>
<td>Serbia</td>
<td>French Guiana</td>
<td>Spain (7; $30/mT)</td>
</tr>
<tr>
<td>Armenia</td>
<td>Slovakia</td>
<td>French Polynesia</td>
<td>Sweden</td>
</tr>
<tr>
<td>Azerbaijan</td>
<td>Slovenia</td>
<td>Greece</td>
<td>Switzerland</td>
</tr>
<tr>
<td>Belarus</td>
<td>Tajikistan</td>
<td>Guadeloupe</td>
<td>United Kingdom (6; $50/mT)</td>
</tr>
<tr>
<td>Bosnia and Herzegovina</td>
<td>Turkmenistan</td>
<td>Iceland</td>
<td>United States (3; $250/mT)</td>
</tr>
<tr>
<td>Bulgaria</td>
<td>Ukraine</td>
<td>Ireland</td>
<td>Uruguay</td>
</tr>
<tr>
<td>Croatia</td>
<td>Uzbekistan</td>
<td>Israel</td>
<td></td>
</tr>
<tr>
<td>Czech Republic</td>
<td></td>
<td>Italy (9; $30/mT)</td>
<td></td>
</tr>
<tr>
<td>Estonia</td>
<td></td>
<td>Japan (4; $60/mT)</td>
<td></td>
</tr>
<tr>
<td>Georgia</td>
<td></td>
<td>Luxembourg</td>
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<tr>
<td>Hungary</td>
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<td>Malta</td>
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<tr>
<td>Kazakhstan</td>
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<td>Martinique</td>
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<tr>
<td>Kyrgyzstan</td>
<td></td>
<td>Mayotte</td>
<td></td>
</tr>
<tr>
<td>Latvia</td>
<td></td>
<td>Netherlands (20; $10/mT)</td>
<td></td>
</tr>
<tr>
<td>Lithuania</td>
<td></td>
<td>New Caledonia</td>
<td></td>
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<tr>
<td>Moldova</td>
<td></td>
<td>New Zealand</td>
<td></td>
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<tr>
<td>Mongolia</td>
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<td>Norway</td>
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<tr>
<td>Montenegro</td>
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<td>Portugal</td>
<td></td>
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<tr>
<td>North Macedonia</td>
<td></td>
<td>Reunion</td>
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<tr>
<td>Poland</td>
<td></td>
<td>San Marino</td>
<td></td>
</tr>
<tr>
<td>Romania</td>
<td></td>
<td>Singapore</td>
<td></td>
</tr>
</tbody>
</table>

| Latin America and Caribbean                 |                                 |                     |                         |
| Antigua and Barbuda                         |                                 |                     |                         |
| Bahamas                                     |                                 |                     |                         |
| Barbados                                    |                                 |                     |                         |
| Belize                                      |                                 |                     |                         |
| Bolivia                                     |                                 |                     |                         |
| Brazil (13; $20/mT)                         |                                 |                     |                         |
| Colombia                                    |                                 |                     |                         |
| Costa Rica                                  |                                 |                     |                         |
| Cuba                                        |                                 |                     |                         |
| Dominican Republic                          |                                 |                     |                         |
| Ecuador                                     |                                 |                     |                         |
| El Salvador                                 |                                 |                     |                         |
| Grenada                                     |                                 |                     |                         |
| Guatemala                                   |                                 |                     |                         |
We also test the sensitivity of these monetized results to a 20-year mortality cessation lag (Table S2). This lag accounts for the time duration between initial exposure and death and has historically only been applied in U.S. EPA analyses for deaths resulting from particulate matter exposure. Mortality resulting from long-term ozone exposure may result in similar health outcomes as particulate matter, including chronic respiratory disease and lung cancer. To implement the cessation lag, we distribute the annual mortality counts from the BenMAP webtool, using the lags in Table S2. The cessation-adjusted mortality counts are then monetized and discounted using the same approach as described above. While most ozone-attributable deaths are estimated to occur in 2020 (Figure S4), implementation of the cessation lag distributes these to later years resulting in net present damages of $1600/ton CH₄ (2% Ramsey), which is roughly a 2.5% reduction in damages compared to the central estimate presented in the main text.
Table S2. 20-year mortality cessation lag

<table>
<thead>
<tr>
<th>Year(s)</th>
<th>Fraction of deaths attributable to initial O₃ exposure that occur in each subsequent year</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>30%</td>
</tr>
<tr>
<td>1-4</td>
<td>12.5%</td>
</tr>
<tr>
<td>6-19</td>
<td>1.3%</td>
</tr>
</tbody>
</table>

Section S6. Methane-Ozone Mortality Model – Reduced Form Tool

As described in the main text, due to the computational requirements to run the global cloud-based BenMAP tool under multiple future scenarios, we additionally develop an R-based reduced form tool to test the sensitivities of the global NPV to changes in socioeconomic and precursor emission projections. The reduced form tool leverages the near linear relationships between changes in long-term O₃ exposure levels and population and background mortality characteristics with changes in attributable mortality.

To evaluate the reduced form tool, we run a series of select additional BenMAP simulations for specific individual RFF-SP projections. Running the reduced form tool for the same projection number reveals that the global respiratory-related mortality estimates from the reduced form tool are within 0.5% of the BenMAP calculated results for all tested simulations. Individual year- and projection-specific estimates may be greater. The country-level mortality counts from the reduced form tool and from the original BenMAP runs are then monetized and discounted using the same methodology. Therefore, the BenMAP derived mortality results provide the most accurate respiratory-related mortality estimates for a specific future scenario, but the development of the reduced form approach allows us to quickly test additional sensitivities of the NPV to a large range of future conditions.

The reduced form tool has also been designed to facilitate the calculation of NPV (i.e., SC-CH₄) associated with a custom methane emissions pulse under any socioeconomic scenario. The model currently allows users to specify parameters such as the methane emission pulse size, methane perturbation lifetime, pulse year, the cessation lag (if implementation is selected), the income elasticity, and value of a statistical life. Other inputs include 2020-2100 projections of country-level population, background respiratory related mortality, and GDP. As population and background mortality are inherently linked, the tool is currently equipped to run any of the 10,000 probabilistic public RFF-SP scenarios [Rennert et al., 2022b]. Lastly, the user may also choose to input a projection of country-level NOₓ emissions (in megatons/year) or a single NOₓ emission scaling factor. If a scaling factor is chosen, NOₓ levels in each country are held constant over time at the 2015 emissions levels used in the original UNEP/CCAC simulations, multiplied by the scaling factor (e.g., new NOₓ = NOₓ scalar * original NOₓ). In either case, the timeseries of NOₓ emissions are used in the tool to calculate the change in methane-O₃ production efficiency, following the ΔO₃ response/NOₓ emissions relationships in Eq. 6 in the main text, derived as part of the original UNEP/CCAC Assessment [UNEP/CCAC, 2021].
References


International Futures (IFs) modeling system Version 7.88, Pardee Center for International Futures, Josef Korbel School of International Studies, University of Denver, Denver, CO, https://korbel.du.edu/pardee/international-futures-platform/download-ifs.


