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Estimating the Social Cost of Non-CO_2 GHG Emissions: Methane and Nitrous Oxide

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Alex L. Marten[*,†] Stephen C. Newbold[‡]

February 13, 2012

Abstract

Many estimates of the social cost of CO_2 emissions ($SCCO_2$) can be found in the climate economics literature. However, to date far fewer estimates of the social costs of other greenhouse gases have been published, and many of those that are available are not directly comparable to current estimates of the $SCCO_2$. In this paper we use a simplified integrated assessment model that combines MAGICC and (elements of) DICE to estimate the social costs of the three most important greenhouse gases—CO_2, CH_4, and N_2O—for the years 2010 through 2050. Insofar as possible, we base our model runs on the assumptions and input parameters of the recent U.S. government inter-agency SCC working group. We compare our estimates of the social costs of CH_4 and N_2O emissions to those that would be produced by using the $SCCO_2$ to value the "CO_2-equivalents" of each of these gases, as calculated using their global warming potentials (GWPs). We examine the estimation error induced by valuing non-CO_2 greenhouse gas emission reductions using GWPs and the $SCCO_2$ for single- and multi-gas abatement policies. In both cases the error can be large, so estimates of the social costs of these gases, rather than proxies based on GWPs, should be used whenever possible. However, if estimates of the social cost are not available the value of non-CO_2 GHG reductions estimated using GWPs and the $SCCO_2$ will typically have lower absolute errors than default estimates of zero.

Keywords: social cost of carbon, global warming potential, integrated assessment

JEL Classification: Q54, Q58

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1 Introduction

The social cost of carbon dioxide ($SCCO_2$) has become a common metric in estimating the benefits associated with incremental reductions of carbon dioxide emissions.[1] The $SCCO_2$ has been widely studied (see Pearce (2003) for a review) and researchers have produced a large set of varied estimates (Tol, 2007). Newly developed estimates of the $SCCO_2$ are now being used to assess the benefits of CO_2 emission reductions associated with U.S. government regulations.[2] However, recent climate policy analyses have been unable to quantify the benefits of reductions in non-CO_2 greenhouse gas (GHG) emissions due to a lack of comparable social cost estimates for these gases. This paper begins to fill this gap by calculating an internally consistent set of estimates of the social costs of CO_2, CH_4, and N_2O, based on most of the assumptions used by the United States Government Interagency Working Group on the Social Cost of Carbon (USG (2010), hereafter, the "SCC working group"). We also compare the use of direct estimates of the social costs of non-CO_2 GHGs to alternative estimates suggested by some analysts (e.g., Price et al. (2007)) based on global warming potentials (GWPs), which measure the contribution of non-CO_2 GHG emissions to a long run measure of atmospheric radiative forcing relative to that of CO_2.

The paper is structured as follows. In Section 2 we review the literature on the "social cost of carbon [dioxide]," including a brief recap of the recent SCC working group. We also review the much smaller literature on the social costs of other greenhouse gases, including CH_4 and N_2O, and discuss the small set of previous studies that have examined the implications of using GWPs to translate non-CO_2 GHGs into "CO_2-equivalents" for use in economic analysis. Section 3 describes the integrated assessment framework that we use to produce estimates of the social costs of CO_2, CH_4, and N_2O, which combines a climate model (MAGICC, Wigley and Raper (1992), Wigley (2005)) with elements of one of the three integrated assessment models used by the SCC working group (DICE, Nordhaus and Boyer (2000), Nordhaus (2008)). In Section 4 we present our main results, starting with our direct estimates of the social costs of all three GHGs. We then use these estimates to calculate what Samuel Fankhauser denoted as the "global damage potentials" (GDPs) for CH_4 and N_2O, for comparison to their respective GWPs. The degree to which the GDPs of these gases diverge from their GWPs, combined with the shares of the overall GHG emission reductions attributable to each gas under a particular policy, will determine the error in GWP-based benefit estimates. We calculate the magnitude of this error over a wide range of hypothetical mixed-GHG emission reduction policies, and we compare

[1] Much of the previous literature has used the term "SCC" to refer to the social cost of carbon dioxide whether reported in tons of C or CO_2. In this paper we must be more specific since we are discussing the social cost of other greenhouse gases, including another carbon-based molecule, methane.

[2] New rules using the $SCCO_2$ in analysis include the Department of Energy rule on energy conservation standards for small electric motors and the joint U.S. Environmental Protection Agency and U.S. National Highway Traffic Safety Administration (NHTSA) rule on light-duty vehicle greenhouse gas emission and corporate average fuel economy standards. The regulatory impact analysis (RIA) for the regulation of efficiency standards for small electrical motors may be found at http://www1.eere.energy.gov/buildings/appliance_standards/commercial/small_electric_motors.html, and the RIA for the light-duty vehicle rule is available at http://www.epa.gov/oms/climate/regulations.htm.

these results to the error induced by excluding non-CO_2 GHGs from the analysis altogether. We conclude in Section 5 with a brief summary and discussion of the potential policy implications of our results.

2 Background

The social cost of carbon dioxide, $SCCO_2$, represents the present value of the future damages that would arise from an incremental unit of CO_2 (typically one metric ton) being emitted in a given year. In principle, the $SCCO_2$ summarizes the impacts of climate change on all relevant market and non-market sectors, including agriculture, energy production, water availability, human health, coastal communities, biodiversity, and so on. As such, estimates of the $SCCO_2$ play an important role in assessing the benefits of policies that result in reductions of CO_2 emissions. $SCCO_2$ estimates are typically calculated using integrated assessment models (IAMs), which combine simplified models of the climate system and the economy, including the key feedbacks between the two. Small and not-so-small differences in the structural assumptions and the underlying empirical studies used for parameter calibrations among IAMs have led to a wide range of published $SCCO_2$ estimates, from roughly \$0 to \$100 per metric ton of CO_2 (NAS, 2009).

In 2009 the U.S. government undertook an interagency process to establish consistency across federal agencies when valuing incremental CO_2 emission changes in regulatory impact analyses (RIAs). Towards this end, the SCC working group used three widely known IAMs and imposed consistency across several key inputs, including the socio-economic-emission scenarios, discount rate, and climate sensitivity probability distribution. To represent some of the uncertain model inputs, the SCC working group considered five socio-economic-emission scenarios and three discount rates. In the end, the SCC working group selected four estimates of the $SCCO_2$ for use in upcoming RIAs: \$5, \$21, \$35, and \$65. These values are reported in 2007 dollars, apply to emission reductions in 2010, and grow over time at 1-4% per year (USG (2010) Table 4). The first three values are the average estimates across all IAMs and scenarios using discount rates of 5%, 3%, and 2.5% per year, respectively. The last estimate is the 95th percentile across all models and scenarios using a discount rate of 3% per year. These estimates are intended to be used in RIAs for all U.S. federal agency regulations that result in marginal changes in CO_2 emissions.[3] The SCC working group did not provide estimates of the social costs of non-CO_2 GHGs, though they noted that such values will be important for future policy analyses.

The few estimates of the marginal social costs of other GHGs that are available in the climate economics literature rely on outdated modeling assumptions or are otherwise incompatible with recent $SCCO_2$ estimates. For example, some previous studies primarily focused on marginal emission reductions during the mid 1990s and sometimes the early 2000s (Kandlikar (1995), Tol et al. (2003), and Hope (2005)). With the exception of Fankhauser (1994), no

[3] The $SCCO_2$ may not give an accurate estimate of total benefits if applied to large, or "non-marginal," emission reductions, so analyzing large policies may require tailored applications of the IAMs to each policy scenario.

estimates were provided for the years currently of concern to policy makers, and in most cases only a single time period was considered. Extrapolating these estimates to current and future years is not possible without additional assumptions. Furthermore, many of the previous estimates (Kandlikar (1995), Hammitt et al. (1996), and Tol et al. (2003)) were based on reference scenarios that are nearly 20 years old and have now been superseded by newer studies (Houghton et al. (1992), and Nakicenovic and Swart (2000)). The most recently published estimates of the social cost of non-CO_2 GHGs are values for CH_4 produced by Hope (2005) using the integrated assessment model PAGE95. However, PAGE95 is substantially different than the current version of the PAGE model (Plambeck and Hope (1996), Plambeck et al. (1997), and Hope (2006)). In recent years much attention has been paid to the social costs of CO_2, both in terms of updating the integrated assessment models to reflect progress in our understanding of the physical impacts and economic damages from climate change, and exploring the sensitivity of $SCCO_2$ estimates to important modeling assumptions (Nordhaus (2010), Narita et al. (2010), Hope (2009)). Similar attention to non-CO_2 greenhouse gases would be of great benefit to policy analysts who are currently working to assess the impacts of regulations that affect more than just CO_2 emissions.

In the interim it may seem that an easy solution would be to simply convert non-CO_2 GHGs to "CO_2-equivalents" (CO_2-e) using their respective global warming potentials (GWPs) and then value these with the $SCCO_2$. This approach has been suggested by the U.K. Department for the Environment, Food, and Rural Affairs (Price et al., 2007). While a number of previous studies have shown that this simple solution may be inaccurate (Reilly and Richards (1993), Schmalensee (1993), and Fankhauser (1994)), other studies have shown that in cost-effectiveness analyses, where the aim is to minimize the cost of reaching a concentration or temperature stabilization target in some future year, the increased cost required to reach the target due to using proxy trading ratios based on GWPs might be relatively small (O'Neill (2003), Johansson et al. (2006), and Aaheim et al. (2006)).

The goal of developing metrics such as the GWP has been to define a standard relationship between GHGs which represents their relative impact at a particular link along the chain: concentration changes $\rightarrow$ radiative forcing $\rightarrow$ climate impacts $\rightarrow$ socio-economic and environmental impacts $\rightarrow$ economic damages (e.g., O'Neill (2000), Smith and Wigley (2000), and Shine et al. (2005)). The GWP measure was developed to characterize the relationship between the first two links, concentrations and radiative forcings, in part based on a desire to keep the natural science and economic aspects separate (O'Neill, 2003). However, since its inception the GWP metric has been criticized on both scientific and economic grounds for reasons such as its arbitrary time horizon and use of an unrealistic constant concentration scenario.[4] However, despite these shortcomings, GWPs still are used in climate change policy studies, probably due to their simple interpretation and transparent definition and the complexity of alternative measures (Shine et al., 2005).

[4]We refer the interested reader to O'Neill (2000) and Fuglestvedt et al. (2003) for a more complete review of criticisms against GWPs.

The continued use of GWPs has lead to a few recent studies that investigate the magnitude of errors that result from the use of this metric. For example, cost effectiveness studies by O'Neill (2003), Johansson et al. (2006), and Aaheim et al. (2006) have examined the economic implications of using GWPs as the exchange rate within a multi-gas cap-and-trade market as opposed to optimally allocating abatement across GHGs. The GWP approach is known to be suboptimal since holding the trading ratios constant at GWPs will fail to capture the temporal nature of the problem. For example, current emissions of short-lived gases will have a negligible influence on a far-future target, and therefore forcing the trading ratio to be equal in all periods to the GWP will over-value, and in turn lead to over-abatement of, short lived gases in the near term. However, in all cases these authors find that the GWP approach lead to only a modest increase in the overall cost of reaching the target (approximately 4% in Johansson et al. (2006) for a 2 ^{O}C stabilization and 2% in O'Neill (2003) for a 550 ppmv CO_2-e stabilization). This relatively small error can be partly understood by noting that the GWP appears to measure the relative impact of the gases at, or near, the appropriate link in the chain discussed above. That is, for a CO_2-e concentration target, by definition, GWPs will provide the correct trading ratio at the target date. For a temperature target the relevant end point is only one link further along the chain from radiative forcings, so if the climate model used in the analysis considers the relationship between temperature change and radiative forcing to be approximately linear and temperature adjusts relatively quickly then little additional error will be introduced by using GWPs. Johansson et al. (2006) suggested that the steepness of the marginal abatement cost curves is also important in explaining the relatively small loss in cost-effectiveness. This is because in the future when abatement is high and the majority of costs are borne, large changes in the marginal costs will lead to relatively small changes in the levels of abatement. Therefore at this point, a small change to the trading ratio leading to a small change in the relative marginal costs, will result in only a small change to the distribution of abatement across gases.

Unfortunately neither of these factors are relevant when comparing the relative social benefits of emission reductions across GHGs. Not only is there no saving grace analogous to the exponential curvature of marginal abatement costs, but in this case the relevant point in the chain is unequivocally the final endpoint that is associated with economic damages. This is especially problematic given the complexity of the connections along this chain. To see why, we can review the relationship between global warming potential and social costs, following an approach similar to that of Kandlikar (1996).

The GWP measures the radiative effect of a given gas relative to a reference gas over a specified time horizon using the ratio of time integrated radiative forcing that results from the instantaneous release of one additional unit of a compound to that of one additional unit of a reference gas (commonly CO_2) (Ramaswamy et al., 2001). Specifically, the GWP over a time horizon of J years for gas X using CO_2 as the reference gas is

$$GWP = \frac{\int_{\tau=t}^{t+J} \frac{\partial R_\tau}{\partial X_t} d\tau}{\int_{\tau=t}^{t+J} \frac{\partial R_\tau}{\partial CO_{2,t}} d\tau}, \tag{1}$$

where R_t is the total radiative forcing in year t along a pre-defined reference path of emissions of both gases. For comparison, the (consumption-equivalent) social cost of GHG X in year t is

$$SCX_t = \int_{\tau=t}^{t+H} \frac{\partial C_\tau}{\partial X_t} e^{-r(\tau-t)} d\tau,$$

where H is the time horizon of the benefit-cost analysis, C_t is aggregate consumption in year t [$], and r is the discount rate.[5]

Now we can ask, under what conditions would the social cost of gas X be equal to its CO_2-e counterpart multiplied by the $SCCO_2$? To address this question, we can identify a series of simplifying assumptions that will ultimately lead to an equivalence between these two quantities. Then we can ask whether this set of simplifying assumptions is likely to hold in reality, at least to a close enough approximation for the purpose of policy analysis.

The following series of simplifying assumptions is sufficient to make the social cost of gas X equal to its GWP multiplied by the social cost of carbon dioxide: 1.) aggregate consumption in year t is affected only by the temperature anomaly in year t (not the rate of change of temperature or temperature anomalies in previous years), 2.) there is no time lag in the response of the atmospheric temperature to changes in radiative forcing, 3.) the reference emissions scenario for the benefit-cost analysis is the same as that used to calculate the GWP, 4.) the time horizon used for the benefit-cost analysis is the same as that used to calculate the GWP, 5.) the discount rate is zero, 6.) the temperature change is directly proportional to radiative forcing, and 7.) the loss in aggregate consumption is directly proportional to the temperature anomaly.

To see why these assumptions are sufficient to make $SCX_t = GWP \times SCCO_2$, note that assumptions 1 and 2 allow us to re-write the social cost of gas X as

$$SCX_t = \int_{\tau=t}^{t+H} \frac{\partial C_\tau}{\partial T_\tau} \frac{\partial T_\tau}{\partial R_\tau} \frac{\partial R_\tau}{\partial X_t} e^{-r(\tau-t)} d\tau. \tag{2}$$

Assumption 3 means that the ${\partial R_\tau}/{\partial X_t}$ terms in expressions (1) and (2) will be equivalent, and assumption 4 means that $J = H$. Assumption 5 means that $r = 0$, so the discount factor in expression (2) equals one for all time periods.

[5]The SCX_t can be interpreted as the amount of money that, if set aside in year t, would be just sufficient to finance compensation payments for the stream of climate damages in all future years from one additional unit of emissions of GHG X in year t . Under this interpretation the discount rate r would be the interest rate that could be earned on such a hypothetical "trust fund".

Assumptions 6 and 7 mean that $\partial T_t/\partial R_t = b$ and $\partial C_t/\partial T_t = a$ for all time periods. Putting all of this together, expression (2) simplifies to

$$SCX_t = \int_{\tau=t}^{t+J} ab \frac{\partial R_\tau}{\partial X_t} d\tau, \tag{3}$$

which, when divided by the analogous expression for CO_2, leads back to expression (1).

So here is a route to the desired result, but how realistic are the simplifying assumptions that are required to reach it? Each of the first six assumptions is unrealistic on its own, so this full package of assumptions would seem to be highly unrealistic. Specifically, the loss of consumption in any year t may depend on the temperature change in all years up to year t (as in several common integrated assessment models including FUND (Tol, 2002) and DICE (Nordhaus and Boyer, 2000)); the atmospheric temperature does not adjust immediately to its long run equilibrium level (Wigley and Schlesinger, 1985); the reference emissions scenario and the time horizon for the benefit-cost analysis typically do not match those used to calculate GWPs (Schmalensee, 1993); in a standard Ramsey framework, a discount rate of zero would require both the pure rate of time preference and the per-capita consumption growth rate (or the elasticity of the marginal utility of consumption) to equal zero (Weitzman, 2001); and economic losses generally are not modeled as a simple linear function of temperature (Nordhaus, 1994; Cline, 1992). Of the above simplifying assumptions, only the last is realistic: the equilibrium temperature is typically assumed to be proportional to the radiative forcing (Andronova et al., 2007; Roe and Baker, 2007).

The above set of simplifying assumptions is not necessary for the social cost of gas X to be equal to its GWP multiplied by the social cost of carbon dioxide; it is simply the most straightforward set of sufficient conditions. Nevertheless, it would seem to require a highly unlikely convergence of coincidences for GWP to accurately reflect the differences between $SCCO_2$ and the social costs of other GHGs given the long list of assumptions that diverge substantially from what is typically assumed when estimating the $SCCO_2$. Therefore, it seems that the shortcut offered by the GWP is unlikely to be sufficiently accurate for quantitative policy analysis. Instead, it may be necessary to estimate the social cost of each greenhouse gas directly. The main objective of the remainder this paper is to estimate an internally consistent set of social costs for the three main greenhouse gases, following as closely as possible the approach used by the U.S. government interagency SCC working group, and to examine the errors that could arise from using GWP as a shortcut in estimating the benefits of greenhouse gas emissions reduction policies.

3 Integrated Assessment Framework

The integrated assessment framework we use in this paper is based on a modified version of the DICE model, as used by the SCC working group. We maintain the key aspects of this setup, changing only those features that are necessary to facilitate the computation of the social cost of non-CO_2 GHGs. The main issue that arises when using DICE to examine non-CO_2 gases is that the standard version of the model includes an explicit representation of stocks and flows of CO_2 in the atmosphere, but other GHGs are represented only implicitly in a catch-all "exogenous forcing" variable. To remedy this limitation, we replace the climate sub-model in DICE with the MAGICC climate model, which includes gas-cycle models for CH_4 and N_2O, and in the case of CH_4 captures important interactions with other gases. The resulting framework uses exogenous socio-economic and emissions projections, the MAGICC climate model, a probability distribution over the equilibrium climate sensitivity parameter, and components of the DICE model. This section provides a brief discussion of these elements in turn.

3.1 EMF Socio-Economic and Emissions Scenarios

Following the SCC working group, we use exogenous socio-economic and emissions projections based on the Stanford Energy Modeling Forum (EMF). During EMF study number 22, ten well known modeling groups produced a series of socio-economic and emissions trajectories through 2100, which span a range of business-as-usual (BAU) and policy scenarios. The SCC working group selected four of the BAU scenarios to represent the reference case: the IMAGE, MERGE Optimistic, MESSAGE, and MiniCAM Base reference scenarios. The SCC working group also added a fifth lower-than-BAU scenario in which CO_2-e concentrations stabilize at 550 ppm, to represent the possibility of international action without the U.S. and/or more optimistic abatement technology assumptions. For most scenarios insufficient information is available to model all anthropogenic climate forcings, so in the main body of this paper we examine only the MiniCAM Base reference scenario (Calvin et al., 2009). In the Appendix we examine the other scenarios by using data from the MiniCAM scenario to fill in projections for gases that were not reported as part of the EMF-22 results.

To extend the projections beyond 2100, we follow the strategy of the SCC working group. Specifically, the global population projection is extended by assuming that the growth rate will decline linearly starting in 2100 until it reaches zero in 2200. The growth rate of per capita economic output is assumed to decline linearly from the 2100 level to zero in 2300. The industrial CO_2 emissions projection is extended by assuming that the carbon intensity (CO_2/economic output) growth rate will continue to decline after 2100 at the same rate it averaged between 2090 and 2100. The net CO_2 emissions from land use change is assumed to decline linearly starting in 2100 until it reaches zero in 2200, and the radiative forcings from all other emissions are assumed to remain constant after 2100. [6]

[6]The SCC working group did not specify how post-2100 radiative forcings from all non-CO_2 sources would remain constant at 2100 levels. We approximate this scenario by assuming that CH_4 and N_2O emissions drop to their annual decay rate in 2100 in order to keep the stock constant, and we assume that all other non-CO_2 emissions remain constant at their 2100 levels. Under these assumptions, post-2100 non-CO_2 radiative forcing is always within 2% of 2100 levels, which has a negligible effect on the final marginal social cost estimates.

3.2 MAGICC Climate Module

To estimate the impact of anthropogenic GHG emissions on the climate, we use the Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC). MAGICC is a publicly available set of integrated gas cycle, climate, and ice melt models, which are used to predict changes in climate variables given exogenous emissions projections. As a reduced form model designed to emulate more complex global circulation models, MAGICC represents a good approach to incorporating realistic climate dynamics into integrated assessment frameworks (e.g. Calvin et al. (2009)). The model uses historical emissions in conjunction with the supplied scenario of future emissions to compute the global mean temperature from 1765 to the end of the scenario's time horizon (2300 in this paper). The MAGICC climate model has been extensively used in the Intergovernmental Panel on Climate Change (IPCC) reports (e.g. Houghton et al., 1992, Houghton et al., 2001) and other published research (e.g. Hulme and Viner, 1998, New and Hulme, 2000, Wigley and Raper, 2002, Wigley et al., 2009). In this paper we use the most recent version (5.3) of the model, with all parameters set at their default values except for the equilibrium climate sensitivity.[7]

3.3 Climate Sensitivity

The equilibrium climate sensitivity, $\Delta T^{eq}_{2\times CO2}$, is the change in the equilibrium mean global and annual surface temperature that would result from a sustained radiative forcing, $\Delta R_{2\times CO2}$, equivalent to that produced by a doubling of atmospheric CO_2 over its pre-industrial level, such that given a constant λ,

$$\Delta T^{eq}_{2\times CO2} = \lambda \Delta R_{2\times CO2}. \tag{4}$$

While there is a great deal of uncertainty regarding this value, estimates based on observations and global climate models have found that it very likely lies between 2^{o}C and 4.5^{o}C, though these studies have been unable to eliminate the possibility of higher values (Meehl et al., 2007). Uncertainty surrounding equilibrium climate sensitivity stems in part from uncertainty regarding the magnitude of the climate feedbacks associated with global warming (Bony et al., 2006). Given the inherently non-linear relationship between these feedbacks and the temperature response of the climate, basic theory suggests that the probability density function for the equilibrium climate sensitivity will be heavily skewed towards high values (Roe and Baker, 2007; Roe, 2009), a feature that is commonly found in estimates of the parameter's density function.

To characterize the uncertainty in the equilibrium climate sensitivity, we follow the approach of the SCC working group, which relied mainly on the work of Roe and Baker (2007). The change in equilibrium temperature is assumed to be a function of the reference climate sensitivity parameter, λ_0, working on the change in radiative forcings along

[7] MAGICC version 5.3 as used in this exercise was obtained from http://www.cgd.ucar.edu/cas/wigley/magicc/.

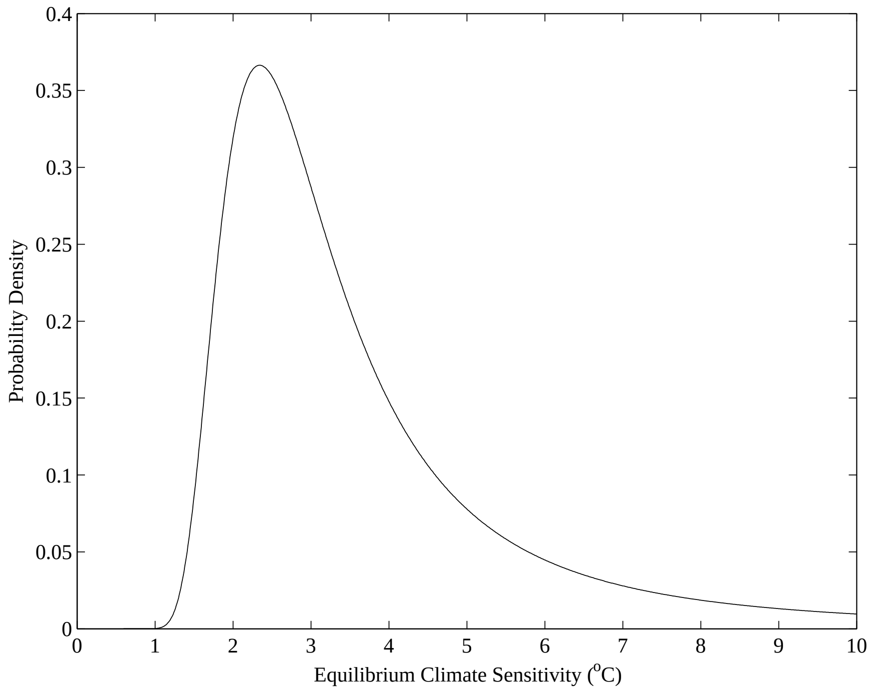


Figure 1: Probability Density Function for Equilibrium Climate Sensitivity (^{O}C)

with a series of climate feedbacks whose total effect is assumed to be proportional to the temperature change by a constant C, such that

$$\Delta T^{eq}_{2\times CO2} = \lambda_0 \left(\Delta R_{2\times CO2} + C \Delta T^{eq}_{2\times CO2} \right). \tag{5}$$

Combining (4) and (5) and defining the sum of feedbacks as $f = \lambda_0 C$, the equilibrium climate sensitivity can be represented as

$$\Delta T^{eq}_{2\times CO2} = \frac{\lambda_0 \Delta R_{2\times CO2}}{1-f}.$$

The reference climate sensitivity parameter, λ_0, represents the predicted temperature response in the absence of any feedback effects and is assumed to be 0.3^{O}C/(w/m^2) , such that $\lambda_0 \Delta R_{2\times CO2} \approx 1.2$ ^{O}C (Roe and Baker, 2007). To represent the uncertainty in the climate feedbacks, f is assumed to be normally distributed with mean μ_f and standard deviation σ_f. To be consistent with the Fourth Assessment Report of the IPCC (Solomon et al., 2007), these parameters were calibrated to ensure that the median of the resulting probability distribution over $\Delta T^{eq}_{2\times CO2}$ was equal to 3^{O}C and that two-thirds of the probability mass lies between 2^{O}C and 4.5^{O}C, with the distribution truncated at 10^{O}C. Based on these conditions the calibrated parameters are $\mu_f = 0.6198$ and $\sigma_f = 0.1841$. The calibrated probability density function of the equilibrium climate sensitivity parameter is shown in Figure 1.

3.4 DICE Economic Module

The DICE integrated assessment model combines a Ramsey-style model of global economic growth, based on a Cobb-Douglas production function with capital and labor as inputs, a basic climate module, and a damage function that relates the average global atmospheric temperature to the loss of economic output. DICE was developed as a dynamic optimization model in which carbon dioxide emissions are endogenously determined by global output, the emissions intensity of production, and the optimized time paths of investment and abatement. Carbon dioxide emissions from economic activities enter a three-box representation of the carbon cycle through which they influence radiative forcings and in turn the atmospheric temperature. To complete the loop, an aggregate damage function links the warming climate to net economic output. For more background on DICE, we refer the interested reader to Nordhaus (1993), Nordhaus and Boyer (2000), and Nordhaus (2008).

To develop a framework consistent with that of the SCC working group, we incorporate a modified version of the DICE2007 model into our integrated assessment framework. Furthermore, we limit our use of DICE to the economic module since we replace the climate component by MAGICC as discussed above. In the economic model, global output, Y_t, depends on "total factor productivity", A_t, population, N_t, physical capital, K_t, and the mean global and annual surface temperature, T_t, through a Cobb-Douglas production function with a "Hicks-neutral" climate damage function:

$$Y_t = A_t K_t^{\gamma} N_t^{(1-\gamma)} \left[1 - D(T_t)\right],$$

where γ represents capital's share of productivity and $D(T_t)$ is the damage (as a fraction of economic output) from climate change consistent with a change in the average global surface temperature above pre-industrial levels, T_t. The rate of saving is assumed to be fixed, so aggregate consumption is $C_t = (1-s)Y_t$.[8] The dynamics of physical capital are defined by the level of investment as determined by the constant savings rate, s, and the depreciation rate, $\delta = 0.1$, such that

$$K_t = sY_t + (1-\delta)K_{t-1}. \tag{6}$$

Population is assumed to be exogenous and is taken from the EMF socio-economic-emissions scenarios directly. The path of total factor productivity, A_t, is calculated from the EMF scenario's projections of economic output and population using the dynamics of capital defined by (6). The initial value, A_0, is set such that the marginal productivity of capital equals 0.1.

[8] The use of the a constant savings rate represents a departure from the standard DICE model where the savings rate is a control variable that is chosen to maximize the net present value of utility for the representative agent. Here again we follow the SCC working group and use $s = 0.22$, which is close to the average optimal savings rate over the first five or so decades on the optimal path in DICE2007.

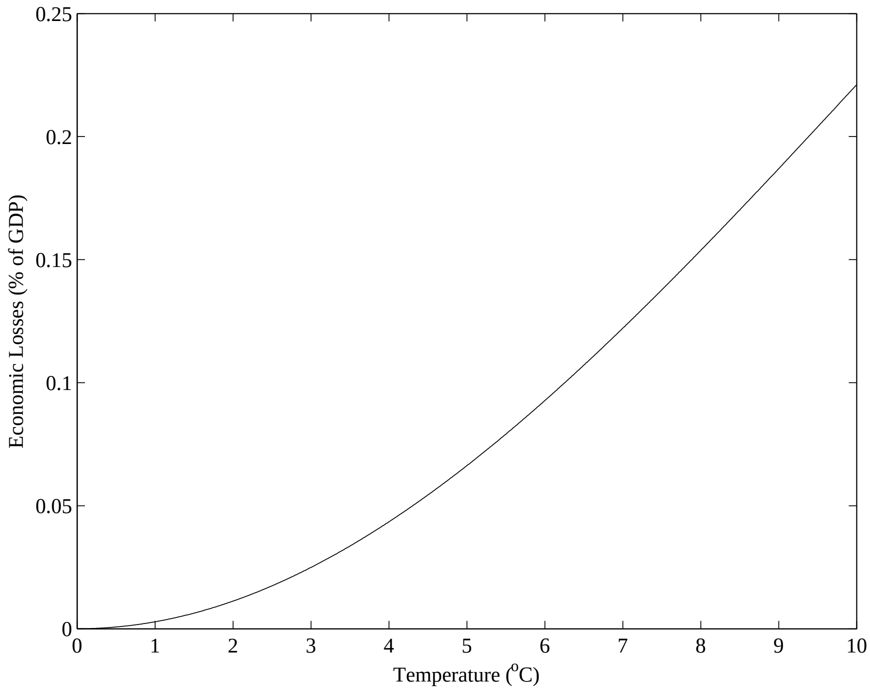


Figure 2: DICE Damage Function

Warming of the climate, as measured by the mean global annual surface temperature above pre-industrial levels, T_t, results in damages expressed as a percentage loss of economic output, Y_t. The damage function in DICE2007 has the following form:

$$D(T_t) = 1 - \frac{1}{1 + aT_t^b}. \tag{7}$$

The parameters of the damage function were calibrated to account for the impacts of climate change on a variety of market and non-market sectors including agriculture, vulnerable industries, coastal areas, human health, environmental amenities net of adaptation, and the willingness to pay to reduce the risk of low-probability high-impact "catastrophic" events (Nordhaus (1994), Nordhaus and Boyer (2000)). In DICE2007, the calibrated damage function parameters are $a = 0.0028388$ and $b = 2$. This gives economic damages equivalent to roughly 2.5% and 9.3% of global economic output if the global average atmospheric temperature is elevated by 3^{O}C and 6^{O}C, respectively. Figure 2 shows the calibrated damage function up to 10^{O}C.

The social cost of GHG X for a specific year, t, is the discounted present value of the loss of consumption due to the release of an extra unit of gas X in year t, i.e.,

$$SCX_t = \sum_{\tau=t}^{t+H} \frac{\Delta C_\tau}{\Delta X_t}(1+r)^{-(\tau-t)},$$

where H is the time horizon of the analysis, r is the discount rate, and ΔC_τ is the difference in aggregate consumption in year τ between the baseline scenario and a perturbed scenario with ΔX_t additional units of emissions of gas X in year t (so SCX_t has units of "\$/unit of emissions in year t"). (This is simply the discrete time analog of the expression for SCX_t given in Section 2.) Following the SCC working group, we treat the discount rate r as constant over the time horizon of the analysis.[9]

We used the integrated assessment framework described above to calculate the expected value of the social cost of CO_2, CH_4, and N_2O in the years 2010 to 2050. The integral used to calculate the expected value, given uncertainty surrounding the equilibrium climate sensitivity, was approximated using numerical quadrature. To accommodate the truncation of the climate sensitivity distribution, Simpson's rule was used with 101 nodal values providing a relatively accurate and efficient approximation of the integral. The number of nodal values was determined based on the level at which the inclusion of additional nodes did not change the social cost when rounded to the nearest dollar. (See Miranda and Fackler (2002) for more information on numerical integration.)

4 Results

Estimates of the expected social cost of marginal CO_2, CH_4, and N_2O emissions in 2010 are presented in Table 1. The average values of the $SCCO_2$ of \$9.4, \$33, \$52 for the three discount rates, and the 95th percentile value of \$74 for the 3% discount rate (2007 U.S. dollars) are comparable to, though somewhat higher than, those produced by the SCC working group using DICE with the MiniCAM base scenario, which were \$8.6, \$29, \$45, and \$58 (USG (2010) Table 3). The differences between our estimates and those of the SCC working group are due to the slightly different behavior of MAGICC relative to the carbon cycle model in DICE. Specifically, in MAGICC 5.3 the CO_2 emissions perturbation exhibits a more pronounced and longer lasting impact on radiative forcing than that of the simplified three-box carbon cycle model in DICE2007. The ranges of the social costs for the non-CO_2 GHGs in 2010 are \$370 to \$2,000 for CH_4 and \$3,500 to \$29,000 for N_2O.

The significantly higher social cost estimates for an additional ton of CH_4 or N_2O in 2010 relative to CO_2 are due to the significantly larger radiative forcing generated by these gases. Figure 3a highlights this difference through the expected temperature change due to an additional metric ton of each gas released in 2010. (Note that the y-axis is in a log10 scale to clearly show the three curves in the same figure.) This figure illustrates two of the important characteristics driving the differences among the social cost estimates of these gases: variation in radiative efficiency and lifespan. The difference in radiative efficiency determines the size of the impact each metric ton has on the

[9] There are many reasons why the discount rate may not be constant over time (e.g., Weitzman (1998), Newell and Pizer (2003), Dasgupta (2008)), but a full discussion of alternative discounting approaches and their impact on the social cost of greenhouse gas emissions is beyond the scope of this paper.

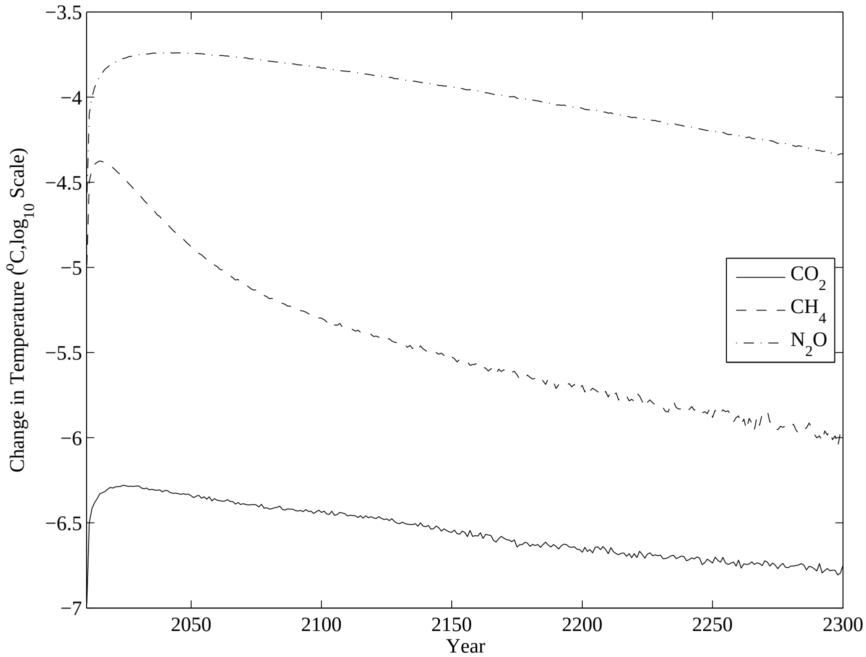
Discount Rate Gas	5.0% Avg	3.0% Avg	2.5% Avg	3.0% 95^{th}
CO_2	9.4	33	52	74
CH_4	370	810	1,100	2,000
N_2O	3,500	13,000	20,000	29,000

Table 1: Social Cost of CO_2, CH_4, and N_2O for 2010 (2007$/tonne)

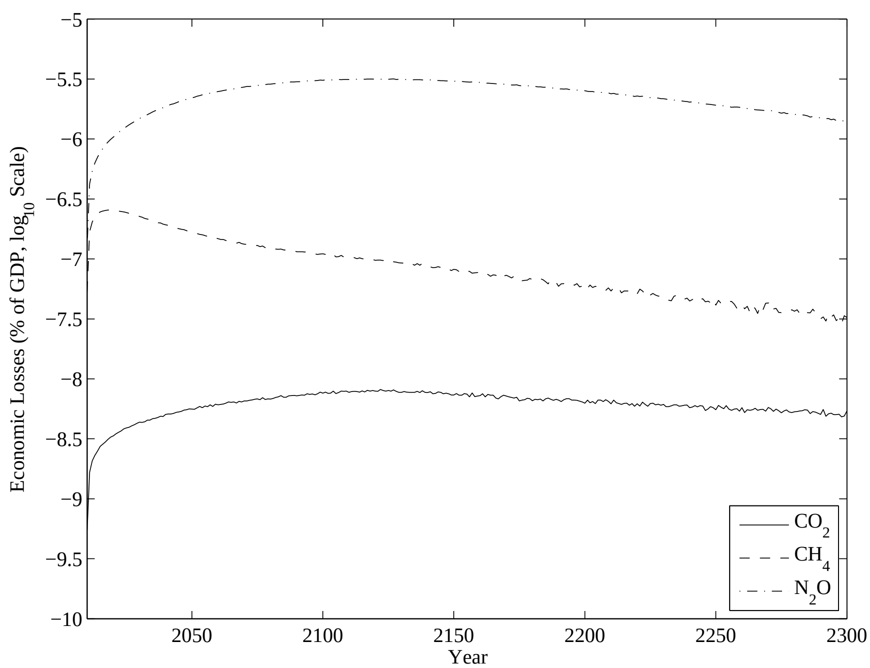
equilibrium temperature, while the difference in atmospheric lifespan determines the length of time over which an additional metric ton of each gas exerts an effect on the global mean temperature and in turn economic damages. For example, the relatively short lifespan of CH_4 causes the temperature impact of a perturbation in 2010 to drop from its peak level by nearly an order of magnitude by 2100, while an analogous effect for a CO_2 perturbation does not occur before the end of the 300 year time horizon.

The impacts of the marginal emissions initially enter the economic model through the damage function in (7), which determine the percentage of aggregate global economic output lost due to the current level of the global mean temperature change. Beyond this direct impact, changes in the climate have a cumulative effect through their influence on investment and in turn future levels of physical capital, i.e., a "capital offset effect." However, for small changes in emissions the direct impacts on economic output will have a similar temporal pattern as their impact on temperature. Figure 3b shows the expected economic losses in a given year as a percentage of global economic output. The y-axis is again presented in log10 scale for easy readability. This figure highlights the important interaction between the temporal dynamics of climate impacts and the non-linearity of the damage function. Rather than peaking at the same time as the temperature impact of the perturbation, the additional economic loss peaks years later, even centuries later as in the case with N_2O versus CO_2. This occurs because the global mean temperature in the reference case is expected to rise over time, in turn causing the direct impact of further temperature increases on economic output also to rise. Therefore, even though the impact of the perturbation on the global mean temperature begins to fall shortly after release, its direct effect on economic output continues to rise. This behavior clearly is an important determinant of the social costs of different GHGs, but it s not captured by an index based solely on the physical impacts of these gases, such as the GWP.

The total stream of damages is determined by the direct economic losses resulting from the additional emissions plus the indirect impacts caused by the capital offset effect. The discount rate clearly plays an important role in aggregating the stream of future damages to a present value estimate of the marginal social cost of emissions, as may be seen from the results in Table 1. However, the influence of the discount rate also depends on the characteristics of the gases. For gases with shorter lifespans, such as CH_4, the majority of the damages will occur earlier in time than



(a) Mean Change in Temperature



(b) Mean Economic Losses

Figure 3: Impact of an Additional Tonne in 2010

those of gases with longer lifespans, such as CO_2 and N_2O. Therefore the social cost of longer-lived gases will be more sensitive to the discount rate than the social cost of shorter-lived gases. For example, the social costs of CO_2 and N_2O are over 450% higher under a 2.5% discount rate than a 5% discount rate, while the social cost of CH_4 is 200% higher.

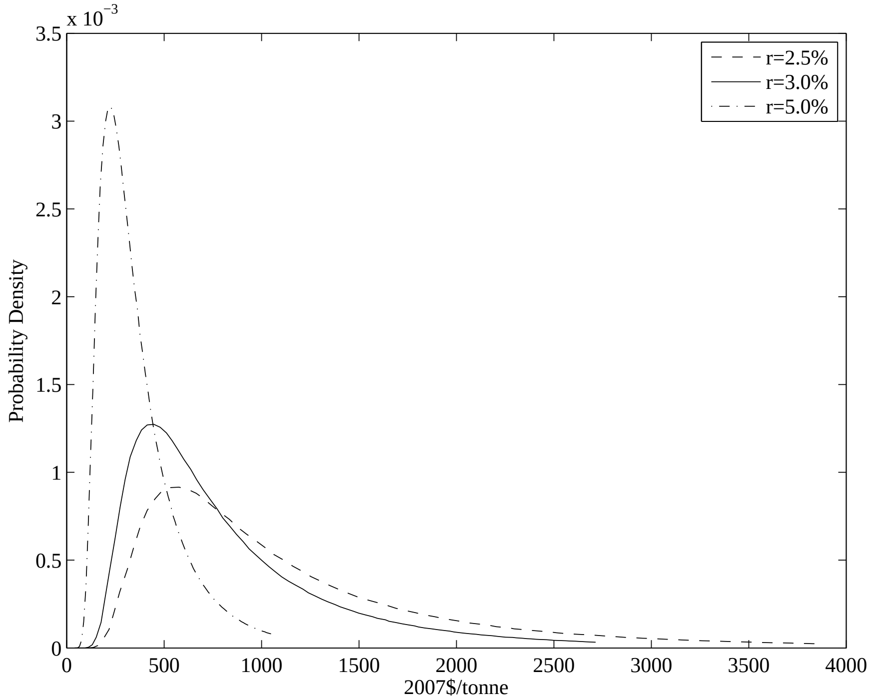
To further illustrate the importance of the discount rate, along with uncertainty regarding the equilibrium climate sensitivity, Figure 4 shows the probability density functions for the social cost estimates of CH_4 and N_2O. As expected, the distributions of the social costs are highly skewed due to the skew of the equilibrium climate sensitivity pdf and the convex damage function. The interaction between the discount rate and the characteristics of the various gases plays an important role in determining both the shape and location of these density functions. As explained above, the longer the lifespan of the gas the greater the impacts it will have on future consumption and therefore the more influential the discount rate will be in determining the location of the density function. As a result the overlap of the pdfs across the three discount rates will be smaller for longer lived gases.

We also used the model to estimate the expected marginal social costs of each gas through 2050. Because both the atmospheric temperature and economic output are projected to increase over time, and because the damage function is a convex function of the temperature, the marginal social costs also will increase over time. Table 2 presents the social cost of an additional metric ton of emissions in the years up to 2050 for CH_4 and N_2O.

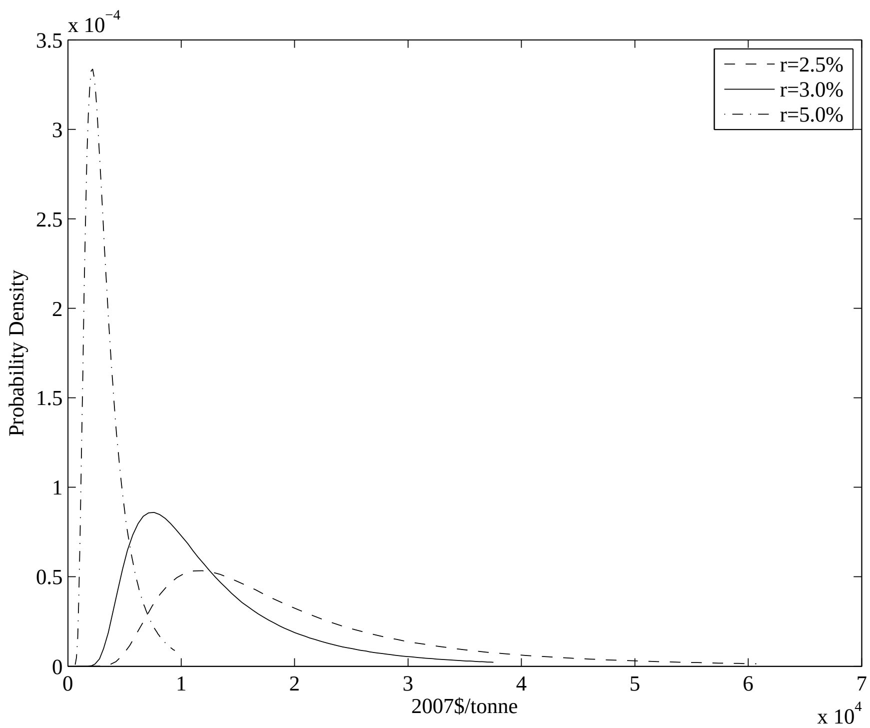
4.1 Error in Using GWPs for Single-gas Policies

With the direct estimates of the social costs of CH_4 and N_2O reported above, we can now examine the error associated with using the GWP to convert emissions reductions into CO_2-e and then valuing these using the $SCCO_2$. Table 3 presents the ratio of the average social cost of CH_4 and N_2O relative to CO_2 for a one metric ton perturbation in the specified year. These values represent the true relationship between the benefits of a marginal reduction in CH_4 or N_2O emissions relative to the same size reduction in CO_2 emissions, i.e., their "greenhouse damage potentials" (GDPs) (Fankhauser, 1994), conditional on the integrated assessment framework laid out in Section 3. By valuing reductions in CO_2-e using the $SCCO_2$ the analyst is implicitly using GWPs to approximate these GDPs. Given that the 100 year GWPs for CH_4 and N_2O, as reported by the IPCC in AR4, are 25 and 298 respectively, it is clear that using the GWP to convert gases to CO_2-e for the purpose of estimating marginal abatement benefits has the potential for significant errors. In 2010 emissions reductions for CH_4 valued using the 100 year GWP could be underestimated by as much as 36% while N_2O could be underestimated by as much as 24%, depending on the discount rate.

As previously noted, the social costs of GHG emissions increase over time because of the higher temperatures and economic output expected in the future and the convexity of the damage function. The estimates of $SCCH_4$ and SCN_2O grow faster than $SCCO_2$ partially due to their initially higher radiative efficiency of CH_4 and N_2O relative



(a) Social Cost of CH_4 for 2010



(b) Social Cost of N_2O in 2010

Figure 4: Probability Distributions

	CO_2				CH_4				N_2O			
Discount Rate	5.0%	3.0%	2.5%	3.0%	5.0%	3.0%	2.5%	3.0%	5.0%	3.0%	2.5%	3.0%
	Avg	Avg	Avg	95^{th}	Avg	Avg	Avg	95^{th}	Avg	Avg	Avg	95^{th}
2010	9.4	33	52	74	370	810	1,100	2,000	3,500	13,000	20,000	29,000
2015	11	37	58	83	450	970	1,300	2,300	4,300	15,000	23,000	33,000
2020	13	42	64	92	550	1,100	1,500	2,700	4,900	17,000	26,000	37,000
2025	15	47	71	100	660	1,300	1,700	3,200	5,800	19,000	29,000	42,000
2030	17	52	78	110	800	1,600	2,000	3,700	6,800	22,000	32,000	47,000
2035	20	58	86	130	950	1,800	2,300	4,200	7,900	24,000	36,000	53,000
2040	23	64	94	140	1,100	2,100	2,700	4,900	9,100	27,000	40,000	59,000
2045	26	71	100	150	1,300	2,500	3,100	5,600	11,000	31,000	45,000	66,000
2050	29	78	110	170	1,500	2,900	3,500	6,400	12,000	34,000	50,000	73,000

Table 2: Social Cost of Marginal CH_4 and N_2O Emissions (2007$/tonne)

Discount Rate	CH_4 5.0% Avg	3.0% Avg	2.5% Avg	3.0% 95^{th}	N_2O 5.0% Avg	3.0% Avg	2.5% Avg	3.0% 95^{th}
2010	39	25	21	27	372	390	392	392
2015	41	26	22	28	375	395	397	395
2020	42	27	23	30	380	400	403	401
2025	44	29	25	31	384	405	408	410
2030	46	30	26	32	390	411	415	415
2035	47	32	27	34	395	417	422	421
2040	49	33	29	36	402	425	430	431
2045	51	35	30	37	408	431	437	438
2050	53	36	32	39	415	439	444	444

Table 3: Social Cost of CH_4 and N_2O Relative to CO_2

to CO_2 and the fact that their marginal forcings decrease slower with the increasing atmospheric stock (square root versus log). As a result the ratio of $SCCH_4$ and SCN_2O to $SCCO_2$ increases with the year of the emission reductions, as seen in Table 3. This implies that the error in using a constant such as GWP to scale the benefits will change over time. For example, using the 100 year GWP to evaluate marginal reductions in CH_4 emissions will underestimate the benefits by up to 36% in 2010, growing to as much as 53% by 2050, depending on the discount rate. For N_2O, using the 100 year GWP underestimates benefits by as much as 24% in 2010 growing to as much as 33% by 2050.

The impact of the discount rate on the ratio of SCX to $SCCO_2$ differs for CH_4 and N_2O. An increase in the discount rate effectively increases the importance of short-term relative to long-term impacts. Therefore the impact of the discount rate on the ratio of SCX to $SCCO_2$ will depend upon the size of the long term impacts for gas X relative to CO_2. Due to the relatively short life span of CH_4 compared with CO_2 the effect of an increase in the discount rate is greater for $SCCO_2$ and in turn the ratio of the two social costs decreases, as seen in Table 3. However, in the case of N_2O the decay of a perturbation's impact on overall radiative forcing is slower than that of a CO_2 perturbation, and in turn an increase in the discount rate will lower the ratio of SCN_2O to $SCCO_2$.

4.2 Error in Using GWPs for Multi-gas Policies

The previous results suggest that using the $SCCO_2$ to value CO_2-e reductions will result in large errors when analyzing policies that will reduce emissions of a single gas such as CH_4 or N_2O. This has significant implications for regulatory analysis of policies where a major source of the benefits are derived from non-CO_2 GHG emission reductions. However, for some policies, such as the recent light duty vehicle rule (EPA, 2010b), reductions of non-CO_2 gases may represent only a minor fraction of the anticipated GHG emission reductions. For such policies, the error induced by valuing the social cost of non-CO_2 gases using GWPs may be small. Therefore, in cases where estimates of the marginal social costs of non-CO_2 GHGs are unavailable, the question becomes whether the error induced by the use of GWPs will be tolerable to the decision-maker. To examine this question, we consider how small the reduction in non-CO_2 emissions, relative to the CO_2 reduction, needs to be for the GWP approach to provide an adequate approximation, as measured by the error in overall abatement benefits.

Consider a policy that will result in emissions reduction for two gases, CO_2 and X. The reduction in CO_2 emissions in period t is denoted as $\Delta CO_{2,t}$ and the reduction in X is assumed to be proportional by a factor of α. Therefore the present value of the benefits of these emission reductions are:

$$PV = \sum_{t=0}^{H} [(\alpha SCX_t + SCCO_{2,t}) \times \Delta CO_{2,t}] \times (1+r)^{-t}.$$

If instead of using estimates of SCX to value the reduction in emissions of gas X, the GWP was used to convert those reductions to CO2-e, the present value of benefits would be estimated as:

$$\hat{PV} = \sum_{t=0}^{H} [(\alpha GWP + 1) \times SCCO_{2,t} \times \Delta CO_{2,t}] \times (1+r)^{-t}.$$

As an illustration, we calculated the size of the overall relative error, $\hat{PV}/PV - 1$, using the 100 year GWP for a generic policy lasting 40 years between 2010 and 2050 in which the level of reductions in CO_2 emissions is constant, $\Delta_t = \Delta$, for all periods.[10] Figure 5a shows the case for a policy in which both CO_2 and CH_4 emissions are reduced. For reference, the dotted vertical line indicates the ratio of global CH_4 to CO_2 emissions, which is roughly 0.011 (Calvin et al., 2009). In the case where r= 3%, the total benefits are underestimated by less than 5% as long as the CH4 reductions are less than 1% of the CO_2 reductions. The error increases rapidly as the ratio of CH_4 to CO_2 reductions, α, increases. This is particularly evident for the case of higher discount rates for which the GWP provides a much worse approximation, as was explained above. In the case where r= 2.5%, the average ratio of $SCCH_4$ to $SCCO_2$ is 26 over the 40 year time horizon. This is very close to the 100 year GWP of 25, so in this case the error remains relatively small regardless of the ratio of emissions reductions between the two gases. Also note that the intersections of the three curves with the vertical dotted line in Figure 5a gives the overall relative error from using GWPs to analyze policies that would reduce CH_4 and CO_2 emissions by a common fraction. In this case these errors are on the order of -1% to -14% depending on the discount rate. In spite of this potential error the approach of valuing CO_2-equivalent emissions may be of use to policy makers, when specific $SCCH_4$ estimates are unavailable, since this approach provides a lower

[10] We also examined a case in which the emission reductions grow linearly over time, in the fashion of a "policy ramp." In this scenario, even with a particularly fast increase in abatement, the requirements for obtaining a given overall error become only slightly stricter.

bound for the abatement benefits and therefore provides an unambiguously more accurate estimate of the total benefits over implicitly assuming an $SCCH_4$ of zero.

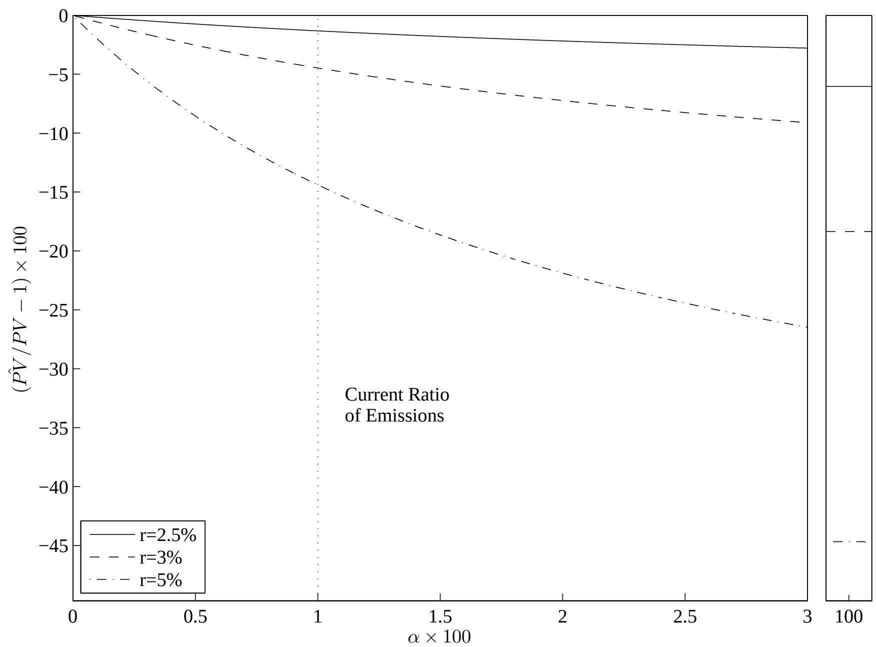
Figure 5b shows the case for a policy that will reduce both CO_2 and N_2O emissions. The dotted vertical line indicates the ratio of current global N_2O to CO_2 emissions, which is around 0.0003 (Calvin et al., 2009). In contrast to the case of CH_4, using GWPs to value N_2O emission reductions results in an error that grows much more rapidly as the share of N_2O reductions increases. By the time N_2O emission reductions are on the order of 0.5% of CO_2 reductions, the GWP approach will underestimate benefits by around 15%-20% compared with an analogous range of 1%-10% for CH_4. This occurs because the level of N_2O benefits are larger in level and therefore also as a percent of total benefits. Therefore even though the GDP for CH_4 is closer to the GWP than it is for N_2O, a markedly smaller proportion of the overall emissions reduction needs to be derived from N_2O to increase the overall error. The other noticeable difference between the cases of N_2O and CH_4 is the relative insensitivity to the discount rate. However, this is not unexpected in light of the discussion in Section 4.1 regarding the impact of the discount rate on these ratios. In Figure 5b all three curves cross the vertical dotted line at nearly the same point. This means that using GWPs to analyze a policy that would reduce N_2O and CO_2 emissions by a common fraction would underestimate the overall benefits by approximately 2.5% independent of the discount rate. At any value of α the GWP approach will provide a lower bound for the benefits of a policy that reduces N_2O, and possibly CO_2, emissions and may therefore provide policy makers with more information than the case in which the SCN_2O is implicitly assumed to be zero.

For policies that affect the emissions of all three gases the magnitude of the bias will depend on not only the overall proportion of CH_4 and N_2O emissions, but also the discount rate being utilized.

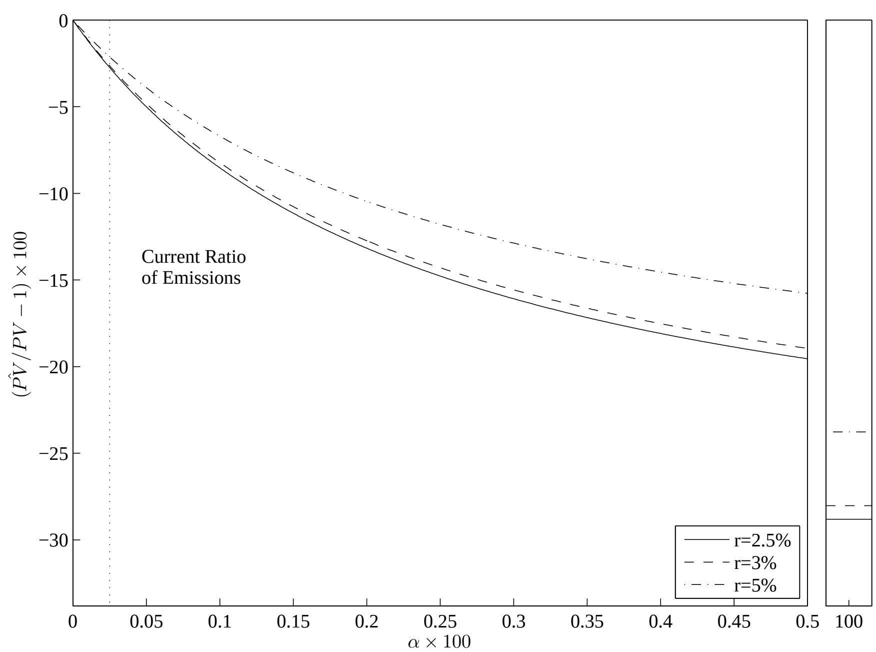
4.2.1 Abatement Benefits of Light-Duty Vehicle Rule

One of the first applications of the new interagency $SCCO_2$ estimates in a RIA was that of the joint rule making between the U.S. Environmental Protection Agency (EPA) and the U.S. National Highway Traffic Safety Administration (NHTSA) on light-duty vehicle greenhouse gas emission and corporate average fuel economy standards (EPA, 2010b). Signed in April of 2010, this rule sets emissions and fuel economy standards for passenger cars, light-duty trucks, and medium-duty passenger vehicles for the model years 2012 through 2016. The rule is expected to reduce the emissions of CO_2, CH_4, and N_2O where Table 4 presents the EPA's emission reduction estimates for the years 2020, 2030, 2040, and 2050 (EPA (2010a) Table 5-26). Therefore the social benefits of the rule will be based on the reduction of emissions for multiple GHGs, however, the economic analysis presented in the RIA only quantifies the benefits associated with CO_2 emission reductions (EPA, 2010a).

The N_2O emission reductions are consistently around 0.0002% of CO_2 reductions, while CH_4 reductions are



(a) Error with CH_4 and CO_2 Abatement



(b) Error with N_2O and CO_2 Abatement

Figure 5: Error in Overall Abatement Benefits Estimate

	2020	2030	2040	2050
CO_2	139,067,814	273,257,576	360,372,017	458,709,558
CH_4	153,944	302,450	398,851	507,687
N_2O	302	575	749	953

Table 4: GHG Emission Reductions from Light-Duty Vehicle Rule (tonnes)

consistently around a 0.1% of CO_2 emission reduction by mass. Ignoring the N_2O reductions for the moment, this policy resembles the illustration above where CH_4 emission reductions were a constant percentage of CO_2 reductions over time. Figure 5a suggests that if GWPs were used to estimate the benefits of CH_4 reductions in this case then the overall benefits would be underestimated by around 1-2%, depending on the discount rate. In fact, comparing the GWP approach and the use of the direct estimates we find that the error associated with valuing CO_2-e reductions is approximately -1% when using a constant 3% discount rate.[11] Using the estimates of $SCCH_4$ and SCN_2O presented in Section 4, the overall error from failing to quantifying the non-CO_2 emission reductions from this rule is approximately 10.6 billion 2007$, which is a relative error of -4%. That is, by using GWPs the relative error could be reduced from -4% to approximately -1%. So this exercise suggests that if direct estimates of the marginal social costs of non-CO_2 GHGs are not available, then the use of GWPs to value non-CO_2 GHG reductions may be preferable to implicitly assuming a value of zero.

5 Concluding Remarks

In this paper we used an integrated assessment framework that combined elements of DICE with the simple climate model MAGICC to develop an internally consistent set of estimates of the social costs of CO_2, CH_4, and N_2O. In developing these estimates, we followed as closely as possible the approach of the recent SCC working group. Our results suggest that the possible alternative of using GWPs to convert marginal non-CO_2 GHG emission reductions into CO_2-e reductions valued using $SCCO_2$ can lead to substantial errors for the abatement benefits of individual gases. Based on our estimates for the $SCCH_4$ and SCN_2O, this approach can underestimate the benefits of current CH_4 emission reductions by up to 35% and the benefits of current N_2O emission reductions by as much as 24%.

The above findings apply to single-gas policies, such as improved leak prevention in natural gas systems, improved waste water treatment practices, or the requirement of specific degasification techniques for coal mining, which would

[11] Since the annual impacts of the rule on GHG emissions were not reported, we derived the inter-decade values by linear interpolation. We also used linear interpolation to determine the effect prior to 2020 assuming that the effect in 2011 will be zero.

mainly reduce CH_4 emissions, and changes to the production process for nitric and adipic acids, which would mainly reduce N_2O emissions (EPA, 2006). We also examined multi-gas policies, where the reductions in CH_4 and N_2O emissions represent only a share of the total GHG emission reductions, for example, the recent light duty vehicle rule by EPA and NHTSA. In these cases, the relative error from using the GWP approach will necessarily be smaller than that for single-gas policies and will of course shrink as the proportion of the GHG emission reduction coming from non-CO_2 gases shrinks. Therefore, depending on the share of non-CO_2 GHG emissions reductions and decision-makers' tolerances for under-estimation errors, when direct estimates of marginal social costs of non-CO_2 GHGs are not available the use of GWPs may be preferred to failing to quantify the benefits of non-CO_2 GHGs altogether.

References

Aaheim, A., Fuglestvedt, J., Godal, O., 2006. Costs savings of a flexible multi-gas climate policy. The Energy Journal (Special Issue# 3), 485–502.

Andronova, N., Schlesinger, M., Dessai, S., Hulme, M., Li, B., 2007. The concept of climate sensitivity: History and development. Human-Induced Climate Change: An Interdisciplinary Assessment.

Bony, S., Colman, R., Kattsov, V., Allan, R., Bretherton, C., Dufresne, J., Hall, A., Hallegatte, S., Holland, M., Ingram, W., et al., 2006. How well do we understand and evaluate climate change feedback processes? Journal of Climate 19 (15), 3445–3482.

Calvin, K., Edmonds, J., Bond-Lamberty, B., Clarke, L., Kim, S., Kyle, P., Smith, S., Thomson, A., Wise, M., 2009. 2.6: Limiting climate change to 450 ppm CO2 equivalent in the 21st century. Energy Economics 31 (2), S107–S120.

Cline, W., 1992. The economics of global warming. Peterson Institute.

Dasgupta, P., 2008. Discounting climate change. Journal of Risk and Uncertainty 37 (2), 141–169.

EPA, U., 06 2006. Global mitigation of non-co2 greenhouse gases. EPA 430-R-06-005.

EPA, U., April 2010a. Final rulemaking to establish light-duty vehicle greenhouse gas emission standards and corporate average fuel economy standards: Regulatory impact analysis.

EPA, U., May 7 2010b. Light-duty vehicle greenhouse gas emission standards and corporate average fuel economcy standards; final rule. Federal Register 75 (88), 25323–25728.

Fankhauser, S., 1994. The social costs of greenhouse gas emissions: an expected value approach. The Energy Journal 15 (2), 157–184.

Fuglestvedt, J., Berntsen, T., Godal, O., Sausen, R., Shine, K., Skodvin, T., 2003. Metrics of climate change: Assessing radiative forcing and emission indices. Climatic Change 58 (3), 267–331.

Hammitt, J., Jain, A., Adams, J., Wuebbles, D., 1996. A welfare-based index for assessing environmental effects of greenhouse-gas emissions. Nature 381 (6580), 301–303.

Hope, C., 2005. The climate change benefits of reducing methane emissions. Climatic Change 68 (1), 21–39.

Hope, C., 2006. The marginal impact of CO2 from PAGE2002: An integrated assessment model incorporating the IPCC's five reasons for concern. Integrated Assessment 6 (1), 19–56.

Hope, C., 2009. How deep should the deep cuts be Optimal CO2 emissions over time under uncertainty. Climate Policy 9 (1), 3–8.

Houghton, J., Callander, B., Varney, S., 1992. Climate change 1992: the supplementary report to the IPCC scientific assessment.

Houghton, J., Ding, Y., Griggs, D., Noguer, M., van der Linden, P., Dai, X., Maskell, K., Johnson, C., 2001. Climate change 2001: the scientific basis. Cambridge University Press Cambridge.

Hulme, M., Viner, D., 1998. A climate change scenario for the tropics. Climatic Change 39 (2), 145–176.

Johansson, D., Persson, U., Azar, C., 2006. The cost of using global warming potentials: Analysing the trade off between CO 2, CH 4 and N 2 O. Climatic Change 77 (3), 291–309.

Kandlikar, M., 1995. The relative role of trace gas emissions in greenhouse abatement policies. Energy Policy 23 (10), 879–883.

Kandlikar, M., 1996. Indices for comparing greenhouse gas emissions: integrating science and economics. Energy Economics 18 (4), 265–281.

Meehl, G., Stocker, T., Collins, W., Friedlingstein, A., Gaye, A., Gregory, J., Kitoh, A., Knutti, R., Murphy, J., Noda, A., et al., 2007. Global climate projections.

Miranda, M., Fackler, P., 2002. Applied Computational Economics and Finance. MIT Press.

Nakicenovic, N., Swart, R., 2000. Special Report on Emissions Scenarios. Cambridge University Press, 598.

Narita, D., Tol, R., Anthoff, D., 2010. Economic costs of extratropical storms under climate change: an application of FUND. Journal of Environmental Planning and Management 53 (3), 371–384.

NAS, 2009. Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use. National Academies Press, Washington, DC.

New, M., Hulme, M., 2000. Representing uncertainty in climate change scenarios: a Monte-Carlo approach. Integrated Assessment 1 (3), 203–213.

Newell, R., Pizer, W., 2003. Discounting the distant future: how much do uncertain rates increase valuations? Journal of Environmental Economics and Management 46 (1), 52–71.

Nordhaus, W., 1993. Optimal greenhouse-gas reductions and tax policy in the" DICE" model. The American Economic Review 83 (2), 313–317.

Nordhaus, W., 1994. Expert opinion on climatic change. American Scientist 82, 45–45.

Nordhaus, W., 2008. A Question of Balance: Weighing the Options on Global Warming Policies.

Nordhaus, W., 2010. Economic aspects of global warming in a post-Copenhagen environment. Proceedings of the National Academy of Sciences 107 (26), 11721.

Nordhaus, W., Boyer, J., 2000. Warming the world: economic models of global warming. The MIT Press.

O'Neill, B., 2000. The jury is still out on global warming potentials. Climatic Change 44 (4), 427–443.

O'Neill, B., 2003. Economics, natural science, and the costs of global warming potentials. Climatic change 58 (3), 251–260.

Pearce, D., 2003. The social cost of carbon and its policy implications. Oxford Review of Economic Policy 19 (3), 362.

Plambeck, E., Hope, C., 1996. PAGE95. An updated valuation of the impacts of global warming. Energy Policy 24 (9), 783–793.

Plambeck, E., Hope, C., Anderson, J., 1997. The page 95 model: Integrating the science and economics of global warming. Energy Economics 19 (1), 77–101.

Price, R., Thornton, S., Nelson, S., 2007. The social cost of carbon and the shadow price of carbon: What they are, and how to use them in economic appraisal in the uk. Tech. rep., Department for Environment, Food, and Rural Affairs.

Ramaswamy, V., Boucher, O., Haigh, J., Hauglustaine, D., Haywood, J., Myhre, G., Nakajima, T., Shi, G., Solomon, S., Betts, R., et al., 2001. Radiative forcing of climate change. In: Houghton, J., Ding, Y., Griggs, D., Noguer, M., van der Linden, P., Dai, X., Maskell, K., Johnson, C. (Eds.), Climate Change 2001: The Scientific Basis. Cambridge University Press, pp. 349–416.

Reilly, J., Richards, K., 1993. Climate change damage and the trace gas index issue. Environmental and Resource Economics 3 (1), 41–61.

Roe, G., 2009. Feedbacks, timescales, and seeing red. Annual Review of Earth and Planetary Sciences 37, 93–115.

Roe, G., Baker, M., 2007. Why is climate sensitivity so unpredictable? Science 318 (5850), 629–632.

Schmalensee, R., 1993. Comparing Greenhouse Gases for Policy Purposes. The Energy Journal 14 (1), 245–256.

Shine, K., Fuglestvedt, J., Hailemariam, K., Stuber, N., 2005. Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases. Climatic Change 68 (3), 281–302.

Smith, S., Wigley, M., 2000. Global warming potentials: 1. Climatic implications of emissions reductions. Climatic Change 44 (4), 445–457.

Solomon, S., Qin, D., Manning, M., Marquis, M., Averyt, K., Tignor, M., Miller, H., Chen, Z., 2007. Climate changee 2007: the physical science basis.

Tol, R., 2002. Estimates of the damage costs of climate change, Part II. Dynamic estimates. Environmental and Resource Economics 21 (2), 135–160.

Tol, R., 2007. The Social Cost Of Carbon: Trends, Outliers And Catastrophes. Working Papers.

Tol, R., Heintz, R., Lammers, P., 2003. Methane emission reduction: An application of FUND. Climatic Change 57 (1), 71–98.

USG, February 2010. Technical support document: Social cost of carbon for regulatory impact analysis under executive order 12866.

Weitzman, M., 1998. Why the far-distant future should be discounted at its lowest possible rate. Journal of environmental economics and management 36 (3), 201–208.

Weitzman, M., 2001. Gamma discounting. American Economic Review, 260–271.

Wigley, T., 2005. The climate change commitment. Science 307 (5716), 1766–1769.

Wigley, T., Clarke, L., Edmonds, J., Jacoby, H., Paltsev, S., Pitcher, H., Reilly, J., Richels, R., Sarofim, M., Smith, S., 2009. Uncertainties in climate stabilization. Climatic Change 97 (1), 85–121.

Wigley, T., Raper, S., 1992. Implications for climate and sea level of revised IPCC emissions scenarios. Nature 357, 293–300.

Wigley, T., Raper, S., 2002. Reasons for larger warming projections in the IPCC Third Assessment Report. Journal of Climate 15 (20), 2945–2953.

Wigley, T., Schlesinger, M., 1985. Analytical solution for the effect of increasing CO2 on global mean temperature. Nature 315, 649–652.

A Results for Additional Socio-Economic-Emissions Scenarios

To define projections of socio-economic-emissions paths the USG Interagency Working Group selected scenarios from the EMF-22 modeling exercise. The scenarios selected included four BAU scenarios and a fifth lower-than-BAU scenario in which CO_2-e concentrations stabilized at 550 ppm. The four BAU scenarios included the IMAGE, MERGE Optimistic, MESSAGE, and MiniCAM Base reference scenarios. The fifth scenario is the average of the stabilization at 550 ppm CO_2-e without overshoot for the same four models.

In the paper we focused on the MiniCAM Base reference scenario due to access to the full suite of emissions projections for this scenario. For the other models EMF only published emissions projections for CO_2, CH_4, and N_2O, while the climate model used in this paper (MAGICC) requires inputs for tropospheric aerosols and halogenated gases as well. In order to get some insight into the difference in SCX estimates across the scenarios, we combine the model specific projections for economic output, population, and CO_2, CH_4, and N_2O emissions with the MiniCAM trajectories for the remaining input gases. This assumption will affect the SCX estimates in two ways, first due to the non-linearity of the damage function the base line temperature will play an important role and this assumption may over or under represent warming for these additional scenarios. Second the atmospheric lifetime of CH_4 will be dependent upon the concentrations of NO_x, CO, and other VOCs.

Discount Rate	CO_2				CH_4				N_2O			
	5.0% Avg	3.0% Avg	2.5% Avg	3.0% 95^{th}	5.0% Avg	3.0% Avg	2.5% Avg	3.0% 95^{th}	5.0% Avg	3.0% Avg	2.5% Avg	3.0% 95^{th}
2010	11	36	57	82	430	910	1,200	2,200	4,000	14,000	21,000	31,000
2015	13	41	63	92	530	1,100	1,400	2,600	4,700	16,000	24,000	35,000
2020	15	46	69	100	640	1,300	1,600	3,000	5,600	18,000	27,000	40,000
2025	17	51	77	110	760	1,500	1,900	3,500	6,500	20,000	30,000	45,000
2030	20	57	84	130	900	1,700	2,200	4,000	7,500	23,000	34,000	50,000
2035	23	63	92	140	1,100	2,000	2,500	4,600	8,700	25,000	37,000	56,000
2040	26	70	100	150	1,200	2,300	2,800	5,200	9,900	28,000	41,000	62,000
2045	29	77	110	160	1,400	2,600	3,200	5,900	11,000	32,000	46,000	69,000
2050	32	84	120	180	1,600	2,900	3,600	6,600	13,000	35,000	50,000	76,000

Table 5: Social Cost of Marginal CH_4 and N_2O Emissions (2007$/tonne) - IMAGE

	CO_2				CH_4				N_2O			
Discount Rate	5.0% Avg	3.0% Avg	2.5% Avg	3.0% 95^{th}	5.0% Avg	3.0% Avg	2.5% Avg	3.0% 95^{th}	5.0% Avg	3.0% Avg	2.5% Avg	3.0% 95^{th}
2010	8	24	35	53	340	700	890	1,600	3,100	9,800	14,000	21,000
2015	10	27	38	58	420	820	1,000	1,900	3,600	11,000	16,000	24,000
2020	11	30	42	64	510	970	1,200	2,200	4,300	13,000	18,000	27,000
2025	13	33	46	71	610	1,100	1,400	2,600	5,000	14,000	20,000	30,000
2030	15	36	50	78	730	1,300	1,600	3,000	5,800	16,000	22,000	33,000
2035	16	40	54	84	860	1,600	1,900	3,500	6,700	18,000	25,000	37,000
2040	18	43	58	90	1,000	1,800	2,200	3,900	7,600	20,000	27,000	41,000
2045	20	47	62	95	1,200	2,000	2,500	4,400	8,700	22,000	30,000	45,000
2050	22	50	66	100	1,400	2,300	2,800	5,000	9,800	24,000	32,000	49,000

Table 6: Social Cost of Marginal CH_4 and N_2O Emissions (2007$/tonne) - MERGE

	CO_2				CH_4				N_2O			
Discount Rate	5.0% Avg	3.0% Avg	2.5% Avg	3.0% 95^{th}	5.0% Avg	3.0% Avg	2.5% Avg	3.0% 95^{th}	5.0% Avg	3.0% Avg	2.5% Avg	3.0% 95^{th}
2010	10	32	47	71	420	850	1,100	2,000	3,700	11,000	17,000	25,000
2015	12	36	52	79	510	1,000	1,300	2,400	4,300	13,000	19,000	29,000
2020	14	40	58	88	620	1,200	1,500	2,800	5,100	14,000	21,000	32,000
2025	16	44	63	98	740	1,400	1,700	3,200	5,900	16,000	23,000	36,000
2030	19	49	69	110	880	1,600	2,000	3,600	6,800	18,000	25,000	40,000
2035	21	54	76	120	1,000	1,800	2,200	4,100	7,700	20,000	28,000	44,000
2040	24	59	82	130	1,200	2,100	2,500	4,700	8,800	22,000	30,000	48,000
2045	27	65	89	140	1,400	2,300	2,800	5,200	9,800	24,000	33,000	52,000
2050	30	70	96	150	1,500	2,600	3,100	5,800	11,000	26,000	36,000	57,000

Table 7: Social Cost of Marginal CH_4 and N_2O Emissions (2007$/tonne) - MESSAGE

	CO_2				CH_4				N_2O			
Discount Rate	5.0% Avg	3.0% Avg	2.5% Avg	3.0% 95^{th}	5.0% Avg	3.0% Avg	2.5% Avg	3.0% 95^{th}	5.0% Avg	3.0% Avg	2.5% Avg	3.0% 95^{th}
2010	9	26	40	63	360	720	920	1,700	3,000	9,000	13,000	21,000
2015	10	30	44	70	440	840	1,100	2,000	3,500	10,000	15,000	24,000
2020	12	33	49	78	530	990	1,200	2,400	4,000	11,000	16,000	27,000
2025	13	37	54	87	630	1,100	1,400	2,700	4,600	13,000	18,000	30,000
2030	15	41	59	96	740	1,300	1,600	3,100	5,200	14,000	20,000	33,000
2035	17	45	65	100	860	1,500	1,900	3,600	5,900	15,000	22,000	36,000
2040	19	50	71	120	980	1,700	2,100	4,000	6,600	17,000	24,000	40,000
2045	22	55	77	130	1,100	1,900	2,300	4,600	7,300	18,000	26,000	44,000
2050	24	60	83	140	1,300	2,200	2,600	5,100	8,100	20,000	28,000	47,000

Table 8: Social Cost of Marginal CH_4 and N_2O Emissions (2007$/tonne) - 550 Stabilization