Technical Support Document on Benefits of Reducing GHG Emissions
U.S. Environmental Protection Agency
June 12, 2008

1. Introduction

This document summarizes technical information and recent but initial work by the EPA on estimating the benefits of greenhouse gas emissions reductions. EPA began developing most of this information in support of the Executive Order 13432 for developing CAA regulations that would reduce GHG emissions from motor vehicles.[1] However, EPA worked on this issue prior to EO13432 and has continued to work on this issue. This technical support document reflects the current state of our thinking. This document is designed to be a self-contained resource of technical background material for the GHG benefits discussions spread across the Advanced Notice and Appendix A, as well as general regulatory consideration of GHG benefits.

Quantifying the benefits of net GHG remissions reductions from an EPA policy requires estimating the value of the projected change in climate change impacts associated with the projected changes in GHG emissions. To develop a methodology for quantifying the benefits of GHG emissions reductions, we first considered the scientific nature of GHGs and climate change, as well as the economic principles that follow from the science. An overview of the scientific nature of GHGs is discussed in sections III and V of the Advanced Notice as well as the Technical Support Document developed to help inform the endangerment discussion. Section III of the ANPR also reviews several of the main economic principles important to consider when evaluating policy options for the regulation of GHGs.

GHG emissions are different in important ways from other emissions regulated under the Clean Air Act. In particular, CO_2 and GHGs have global and very long-run implications compared to conventional air pollutants. “GHGs, for example, CO_2, methane, and nitrous oxide, are chemically stable and persist in the atmosphere over time scales of a decade to centuries or longer, so that their emission has a long-term influence on climate. Because these gases are long lived, they become well mixed throughout the atmosphere.”[2] Therefore, emissions from the U.S. will contribute to climate change impacts in other countries, and emissions in other countries will contribute to climate change impacts in the U.S.

In addition, projected changes in climate could result in or contribute to impacts that exceed thresholds in the dynamics of geophysical and biophysical systems (e.g., large scale climate events such as very large sea-level rise associated with ice sheet deglaciation, as well as the resilience of ecosystems). While scientists still are uncertain about the probability and timing of any given threshold event, the potential detrimental,

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[1] The EO13432 analysis is summarized in the December 14, 2007 draft car and light truck greenhouse gas emissions standard that was provided to the Department of Transportation, National Highway Traffic Safety Administration.

[2] IPCC WGI (2007).

and in some cases catastrophic, nature of such events provides cause for concern among many researchers and policymakers regarding the potential effects of climate change.

Also, given physical inertia in the climate system, as well as inertia in the economic system, substantially altering climate from projected business-as-usual conditions will require large GHG emissions mitigation beyond the mitigation potential of any one country.[3]

Finally, the impacts of climate change are inherently uncertain given uncertainties in socio-economic futures, corresponding GHG emissions, climate responses to emissions changes, and the bio-physical and economic impacts associated with changes in climate.

Since CO_2 and other GHGs mix well in the atmosphere regardless of the location of the source, with each unit of emissions affecting global regional climates, and therefore influencing regional biophysical systems, estimating the benefits of GHG emissions reductions requires first projecting net global GHG emissions and then projecting the changes in the global climate that would result from those emissions. Since the effects of changes in GHG emissions are felt for decades to centuries given the atmospheric lifetimes of GHGs, we also need to estimate projected changes in climate impacts over the lifetime of the GHG and the subsequent climate change inertia in the climate system. Finally, benefits estimates need to reflect the uncertainties associated with global biophysical and economic modeling over a very long time horizon. Therefore, it is important to consider alternative scenarios and ranges of outcomes. Quantifying the monetary and non-monetary benefits of GHG emissions reductions over this spatial and temporal scale is challenging.

The benefits of GHG emissions reductions can be characterized both qualitatively and quantitatively, some of which can be monetized. There are substantial uncertainties in modeling the global risks of climate change, which complicates quantification and benefit-cost assessments. Projected changes in climate variables, such as average temperatures and the frequency of extreme weather events, can serve as meaningful proxies for changes in the risk of all potential impacts, including those that can be monetized, as well as those that have not been monetized but can be quantified in physical terms (e.g., water availability), and those that have not yet been quantified (e.g., forest disturbance) or are extremely difficult to quantify (e.g., catastrophic events such as collapse of large ice sheets and subsequent substantial sea level rise). As such, projected changes in climate variables can provide information that both complements and supplements monetized benefits estimates, where they serve as a first step in quantifying benefits and provide a more expansive characterization of potential changes to climate risks.

The next section explains how the benefits of GHG reductions might be presented in terms of estimated changes in projected climate. After that, we discuss the economic principles relevant to the consideration of monetized benefits of GHG reductions in EPA

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[3] IPCC WGIII (2007).

rulemakings, including a preliminary set of estimates for the marginal benefits of GHG emissions reductions; and finally, we briefly discuss estimation of total benefits.

2. Changes in Global Mean Temperature

Any projected reduction in CO_2 and other GHGs associated with an EPA policy would affect the distribution of climate change projections over decades to centuries. One common indicator of climate change is global mean surface temperature. This section discusses how we can estimate the response in global mean surface temperature to projected net global GHG emissions reductions.

EPA can estimate projected changes in global mean surface temperatures to 2100 using the MiniCAM (Mini Climate Assessment Model) integrated assessment model[4] coupled with the MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) simple climate model.[5] MiniCAM can be used to create the globally and temporally consistent set of climate relevant variables required for running MAGICC. MAGICC can be used to estimate the change in the global mean surface temperature over time resulting from the estimated GHG reductions associated with a policy scenario. Policy scenario temperature projections can then be compared to baseline temperature projections, such as that associated with MiniCAM's U.S. Climate Change Science Program (CCSP) Synthesis and Assessment Product baseline emissions.[6]

To capture some of the uncertainty in the climate system, we can estimate annual changes in global temperatures across the most current Intergovernmental Panel on Climate Change (IPCC) range of climate sensitivities, 1.5°C to 6.0°C.[7] This would produce a range of time paths of global average temperature changes, where each path is associated with a different assumed value for the climate sensitivity. Figure 1 provides an illustration of the kinds of information that could be provided. Figure 1 provides

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[4] MiniCAM is a long-term, global integrated assessment model of energy, economy, agriculture and land use, that considers the sources of emissions of a suite of greenhouse gases (GHG's), emitted in 14 globally disaggregated global regions (i.e., U.S., Western Europe, China), the fate of emissions to the atmosphere, and the consequences of changing concentrations of greenhouse related gases for climate change. MiniCAM begins with a representation of demographic and economic developments in each region and combines these with assumptions about technology development to describe an internally consistent representation of energy, agriculture, land-use, and economic developments that in turn shape global emissions. Brenkert et al. (2003).

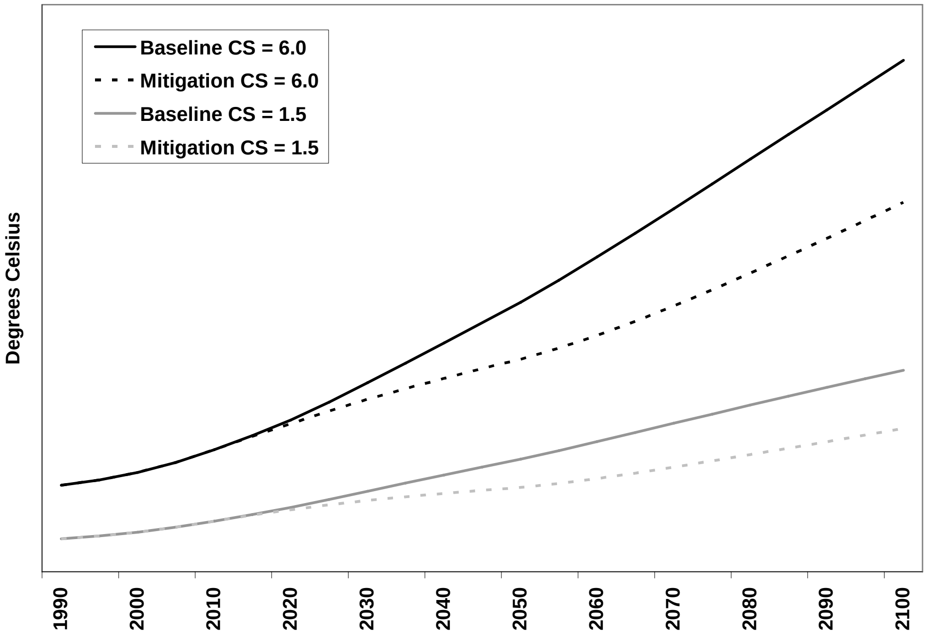
[5] MAGICC consists of a suite of coupled gas-cycle, climate and ice-melt models integrated into a single framework. The framework allows the user to determine changes in GHG concentrations, global-mean surface air temperature and sea-level resulting from anthropogenic emissions of carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), reactive gases (e.g., CO, NOx, VOCs), the halocarbons (e.g. HCFCs, HFCs, PFCs) and sulfur dioxide (SO2). MAGICC emulates the global-mean temperature responses of more sophisticated coupled Atmosphere/Ocean General Circulation Models (AOGCMs) with high accuracy. Wigley and Raper (1992), Raper et al. (1996), Wigley and Raper (2002).

[6] Clarke et al. (2007).

[7] In IPCC reports, equilibrium climate sensitivity refers to the equilibrium change in the annual mean global surface temperature following a doubling of the atmospheric equivalent carbon dioxide concentration. The IPCC states that climate sensitivity is "likely" to be in the range of 2°C to 4.5°C and described 3°C as a "best estimate." The IPCC goes on to note that climate sensitivity is "very unlikely" to be less than 1.5°C and "values substantially higher than 4.5°C cannot be excluded." IPCC WGI (2007).

projections of global mean surface temperatures for hypothetical baseline and mitigation GHG emissions scenarios, and illustrates how near-term emissions reductions can shift the distribution of annual projected global mean surface temperatures down, i.e., annual projected temperatures decrease across all climate sensitivities. Note that the shift in the distribution is expected to be asymmetric, with a larger absolute shift expected for higher climate sensitivities than for lower climate sensitivities. Thus, the distribution is shifting down and becoming more compact. The differences between the projections across climate sensitivity would be expected to widen for larger emissions reductions. Reductions in the distribution of projected global mean temperatures imply reductions in the risks associated with climate change. In the future, we also plan to estimate the shape of the distribution and the estimated shift in the shape in response to rulemakings.[8]

Figure 1: Hypothetical Reduction in Annual Global Mean Surface Temperatures from Baseline with Climate Sensitivities of 1.5 and 6.0



3 Economic principles

Given the atmospheric characteristics of greenhouse gases, several basic economic concepts are relevant when estimating the benefits of GHG emissions reductions and applying the estimates.

3.1 Nature of the Externality

As is the case with many other pollutants, anthropogenic climate change results from a market failure in which emitters of GHG emissions fail to take into account the

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[8] See den Elzen and van Vuuren (2007) for an illustration of shifts in the likelihood of particular temperature outcomes under different mitigation scenarios.

impacts of these emissions on others. However, GHG emissions are different from most air pollutants due to their global and intergenerational externality implications. A ton of GHG emitted from any location or source can result in impacts throughout the globe and across multiple generations. Climate change can therefore be characterized as a global and intergenerational public good. Specifically, the level of climate change experienced by one country or generation has little affect on the climate change experienced by another country or generation (i.e., the provision of the climate change is an "indivisible" good), and no country can be excluded from being affected by changes in climate (i.e., climate change is a "non-excludable" good).

Because GHGs are a global pollutant, economists point out that, to achieve an efficient economic outcome (i.e., maximize global net benefits), countries would need to mitigate up to the point where their domestic marginal cost equals the global marginal benefit (Nordhaus, 2006). Net present value estimates of global marginal benefits internalize the global and intergenerational externalities of reducing a unit of emissions and can therefore help guide policies towards an efficient level of provision of the public good.[9]

Individual countries may only consider the domestic marginal benefit of emissions reductions when making policy decisions.[10] In this case, a country would aim to reduce its domestic GHG emissions up to the point where its domestic social benefit for the next increment of emissions reduction was equal to its domestic cost of that reduction. The mitigation undertaken would generate both domestic benefits and positive externalities for other countries. Thus, the emissions reductions associated with this domestic policy would be lower than if all the international externalities had been internalized. This means there would continue to be a (global) market failure because the remaining domestic emissions are produced without accounting for their full cost to society, i.e., the international (inter-temporal) externalities.

In the economics literature, some posit that if every country considered the GHG mitigation from its domestic marginal benefits perspective, there would be little appreciable mitigation of global GHGs or resulting response in the climate (e.g., Nordhaus, 1995). For this reason, international coordination is often discussed as a necessary step for achieving significant reductions in global GHG emissions, e.g., reductions sufficient for stabilizing atmospheric GHG concentrations.[11] Section III of the

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[9] Both the United Kingdom and the European Commission are following these economic principles in their use of an estimate of the marginal benefit of reducing GHG emissions (i.e., a global social cost of carbon) for valuing the benefits of GHG emission reductions in regulatory impact assessments and cost-benefit analyses (Watkiss et al, 2006). The social cost of carbon is conceptually the marginal cost of an additional unit of carbon emissions. Specifically, SCC is estimated as the net present value of global climate change impacts over 100+ years of one additional ton of GHGs emitted to the atmosphere at a particular point in time.

[10] The domestic marginal benefit accounts for direct impacts on domestic welfare. International welfare effects that might be valued domestically typically are not included.

[11] For example, the President's recent speech discussed the global problem of climate change and the need for action by the major GHG emitting countries. Among other things, President Bush made the following statement in his April 16, 2008 speech: "Yet even if we reduced our own emissions to zero tomorrow, we would not make a meaningful dent in solving the problem without concerted action by all major

Advanced Notice discusses the issue of scope for benefits estimation and asks for comment on this issue.

There is an additional complication if domestic mitigation decisions affect the level of mitigation in other countries. The benefits realized domestically for a domestic mitigation policy may thereby be a function of changes in both domestic and international action. A failure to account for these possible indirect feedback effects could result in errors in benefits estimation. One possible framework for thinking about the potential implications for international action and cooperation is discussed below.

Free riding is always a concern in the provision of public goods, because every individual can enjoy the benefits of other's contributions to providing the public good without contributing themselves. Reducing or slowing climate change is a public good that all regions of the world will experience even if they have not actively participated in decreasing climate change. Individual contributions can still provide some amount of the public good, and may encourage others to contribute. However, free riding behavior tends to lead to an under-provision of the public good (i.e., less than would maximize public net benefits and be economically efficient).[12]

The strategic setting changes when there is a minimum amount of coordination required to provide the good, such as a minimum amount of emissions reductions required to avoid certain threshold (i.e., non-incremental) impacts or reduce risks to "acceptable" levels that cannot be achieved without coordination. With respect to climate change, the threshold could be a temperature level above which there are impacts deemed unacceptable to society[13] or a geophysical threshold associated with a catastrophic event such as the collapse of the West Antarctic Ice Sheet. Each of these examples is associated with implied atmospheric concentrations of greenhouse gases, permissible global emissions, and therefore global emissions reductions from a reference case. These cases can be described as having a minimum contribution level that must be met for the public good to be provided, or a loss avoided. The minimum contribution level can be referred to as a provision point. International coordination is required when individual regions cannot reach the provision point on their own, possibly because it is technically infeasible or astronomically expensive. In this provision point environment, each region that receives a benefit, which could include consideration of international benefits, has an incentive to participate and encourage others to participate.

The economic literature on game theory describes this as an "assurance" game, where cooperation is required to assure provision of the public good.[14] In this setting,

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economies" (http://www.whitehouse.gov/news/releases/2008/04/20080416-6.html, website accessed April 28, 2008).

[12] See Samuelson (1954). Also, note that the experimental economics literature has observed free riding behavior for voluntary contribution settings, but has also observed demand revelation when free riding behavior is the dominant strategy (for a discussion, see Kagel and Roth, 1995, or Davis and Holt, 1993).

[13] The temperature level could be defined by a level above which there is determined to be "dangerous anthropogenic interference," which is a concept of the United Nations Framework Convention on Climate Change.

[14] See, for example, Cornes and Sandler (1996) and Sandler (1997).

participants, which could be countries, are strategically inclined to act as a group—either for full cooperation or no cooperation at all. This is very different from a "prisoner's dilemma" game, where participants are not inclined to cooperate. In the assurance game, there are two possible outcomes, one where it is rational to contribute to providing the good (e.g., with emissions reductions) if it is likely there will be sufficient contributions by others, and the other where it is rational not to contribute at all when it is unlikely that there will be sufficient contributions from others. The presence of the public good provision point has a number of important effects on contribution incentives. First, free riding incentives are diminished but not eliminated, because participants only receive benefits when there are sufficient total contributions.[15] Second, it is economically rational for participants to reveal their plans to contribute to other participants in order to encourage cooperation.[16] Finally, participation is self-sustaining, as each participant will want to continue to participate over time if others continue to participate. This game theoretic structure can be a useful framework for thinking about climate change impact thresholds, emissions reductions, the potential effects of regional action on coordination, and potential overall benefits associated with both domestic and potential international actions.

3.2 Uncertainty and Implications for Applying Benefits

Any exercise of benefits estimation associated with GHG emission reductions is complicated by substantial uncertainties in quantifying many aspects of climate change and climate change impacts, including those associated with characterizing climate-carbon system and ecosystem thresholds and the risk of exceeding them (IPCC WGI, WGII, WGIII, 2007; U.S. Congressional Budget Office, 2005). Uncertainties regarding a host of variables—such as the amount of temperature rise for a given amount of GHG emissions, and rates of economic and population growth in the world's nations over the next 50 or 100 years—may result in a large range of estimates of potential benefits. Similarly, there are substantial uncertainties about the cost of mitigation due to the long time horizon for implementing climate change policies. These include uncertainties about the timing of international participation, and the potential for technological innovations that could increase the emissions reduction feasibility and lower mitigation costs. Uncertainty is compounded by the existence of numerous unquantifiable effects, and by the potential for threshold effects. In situations such as this, EPA typically recommends that analyses consider a range of benefit and cost estimates, as well as the potential implications of non-monetized and non-quantified benefits.

Given the substantial uncertainties in quantifying many aspects of climate change mitigation and impacts, it is difficult to apply economic efficiency criteria, or even positive net benefit criteria. Identifying an efficient policy requires knowing the marginal

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[15] The experimental economics literature characterizes this case as a "provision point," where a minimum level of participation is required in order to provide the public good (Davis and Holt, 1993). This literature has found increased provision and demand revelation performance with provision point mechanisms in both laboratory and actual applications in the field (Bagnoli and Lipman, 1989; Isaac et al., 1989; Bagnoli and McKee, 1991; Rose et al., 2002; Rondeau et al., 2005).

[16] This is quite different from typical incentives for secrecy in contributing to the provision of normally continuous public goods.

benefit and marginal cost curves, such that additional emissions reductions are efficient if the marginal benefits are greater than the marginal costs. However, instead of unique curves, they are wide and partially unknown bands of potential marginal benefits and costs curves. Similarly, total benefits and costs are ranges. As a result, it is difficult to identify the efficient policy, and to assess net benefits.

In situations with large uncertainties, such as climate change and climate change impacts, economics recommends a risk management framework as being appropriate for guiding policy (Manne and Richels, 1992; IPCC WGIII, 2007). In this framework, the policymaker selects a target level of risk and seeks the lowest cost approach for reaching that goal. In addition, it is often recommended that the decision-making process be an iterative one of acting, learning, and acting again. In this context, the value of changes in risk is important. Weitzman (2008) has expressed concern that the standard deterministic modeling approach used by economists to monetize the impacts of climate change does not appropriately characterize the uncertainty and risk related to the possibility of catastrophic events and may lead to a substantial underestimation of the expected benefits from GHG emissions reductions policies. Formal uncertainty analysis may be able to at least partially account for these concerns. It is worth noting that even incremental reductions in global emissions will shift the likelihood of climate change and reduce the risks of climate change, including catastrophic risks.

Economics alone cannot indicate the “correct” amount of GHG mitigation. Judgments about the appropriate mitigation policy can be informed by economics, but also involve important policy, legal, and ethical questions that cannot be answered by economics (as well as consideration of non-quantified benefits). For example, what degree of climate change risk is acceptable for future generations, or people in other countries, when GHG emissions imply irreversible changes in climate? Should domestic unilateral policy actions account for benefits accruing to other countries in the absence of an international agreement governing GHG reductions? Answering such questions involves making unavoidable ethical choices (Broome 1992, 2008). Economic analysis can suggest different ways of approaching these questions, and can provide input on the efficiency, effectiveness, and game theoretic implications of alternatives, but economics alone cannot determine which approach is most acceptable. Similarly, economics cannot answer the question of how much more likely other countries are to agree to stringent control if the U.S. adopts such controls first, or if the U.S. refuses to do so until other countries agree, although game theory can help inform that consideration. Where the Clean Air Act applies, requirements in the Clean Air Act may reflect policy and political considerations in addition to economic efficiency.

3.3 Discounting of Future Costs and Benefits

Lastly, when considering climate change investments, they should be compared to similar investments (via the discount rate). EPA typically discounts future costs or benefits back to the present using a discount rate, where the discount rate represents how society trades off current consumption for future consumption. With the benefits of GHG emissions reductions distributed over a very long time horizon, benefit and cost comparisons are likely to be very sensitive to the discount rate. For policies with relatively short time horizons, up to 30 years or so (i.e., that affect the current generation of people), the analytic approach used by EPA is to use discount rates of 3% and 7% percent at a minimum.[17] A 3% rate is consistent with what a typical consumer might expect in the way of a risk free market return. A 7% rate is an estimate of the average before-tax rate of return to private capital in the U.S. economy.

However, what discount rates are appropriate for discounting social benefits and costs over the longer timeframe relevant for climate change policies? Investments in climate change represent longer-term investments in infrastructure and technologies associated with mitigation, where the returns are avoided impacts over a period of one hundred years and longer. Furthermore, there is a potential for significant impacts from climate change, where the exact timing and magnitude of these impacts are unknown. These factors imply an uncertain investment environment with uncertain economic growth that varies over time.

OMB's Circular A-4 general analytical guidance requests use of constant 3% and 7% discount rates for both intra- and inter-generational discounting and allows for low but positive consumption discount rates if there are important intergenerational benefits or costs (e.g., 1–3% noted by OMB, 0.5–3% by EPA). In this inter-generational context, a three percent discount rate is consistent with observed interest rates from long-term intra-generational investments (net of risk premiums) as well as interest rates relevant for monetary estimates of the impacts of climate change that are primarily consumption effects. A review of the literature indicates that rates of three percent or lower are more consistent with conditions associated with long-run uncertainty in economic growth and interest rates, inter-generational considerations, and the risk of high impact climate damages (which could reduce or reverse economic growth).

In the future, EPA will be exploring ways to account for the fact that regulations can produce both near-term and very long-term costs and benefits. Since the rate of economic growth is likely to change over long time horizons, we are exploring, among other things, explicit modeling of uncertainty in economic growth, as well as other parameters, where interest rates will depend on the realization of economic growth. In this context, we can calibrate the initial interest rate to 3% or 7%, for example, and then simulate economic growth paths into the future. With this approach, near-term effective discount rates will be relatively consistent with near-term cost analysis that uses constant exponential discounting. Over the longer term, investment uncertainty and risk increase, and the effective discount rate will reflect the aggregation of results across alternative futures, where futures with lower discount rates will have greater weight in expected net present value calculations. This approach to discounting has been shown to be conceptually appropriate for greenhouse gas (GHG) emissions-related investments with extremely long-run implications and is not subject to time inconsistency problems.[18]

4. Monetized benefits of GHG emissions reductions

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[17] US EPA (2000); US OMB (2003).

[18] Newell and Pizer, 2001, 2003; Weitzman, 1999; Pearce, 2002.

For any significant regulatory exercise, EPA generally attempts to quantify the benefits of emissions reductions that accrue. This is also the case for benefits from reducing GHG emissions, in spite of the challenges outlined above. In developing the estimation approach described below, we considered the economic principles that directly follow from the scientific nature of GHGs and climate change, as well as the state-of-the-art for estimating climate change impacts. In this section, we describe the approach EPA has taken to develop preliminary estimates of marginal benefits from incremental reductions in GHG emissions. We also interpret the estimates and discuss their potential application in standard setting and total benefits calculations that might occur in the context of a rulemaking.

4.1 Benefit estimates

Different approaches are necessary in quantifying the benefits of incremental versus non-incremental reductions in GHGs. Estimates of marginal benefits, such as the social cost of carbon, can be useful for the former, where global net emissions changes are incremental to a baseline case. Marginal benefit estimates are invalid for large deviations from the baseline, since emissions, socioeconomic, and biophysical conditions will change substantially and deviate from the basic underlying assumptions of the original marginal benefits estimates.[19] In addition, current marginal benefit estimation methods do not account for economic and biophysical interactions and feedbacks, which become increasingly important as emissions reductions increase. Non-incremental emissions reductions require a more comprehensive assessment of impacts that models the change in total benefits and captures changes in economic and biophysical levels, dynamics, and feedbacks in response to the policy.

For incremental emissions reductions, it is conceptually appropriate to use an approach that estimates the marginal value of changes in climate change impacts over time as an estimate for the monetized marginal benefit of the GHG emissions reductions projected for the proposal. The marginal value of GHG emissions is equal to the net present value of climate change impacts over hundreds of years of one additional net global metric ton of GHGs emitted to the atmosphere at a particular point in time. This marginal value is sometimes referred to as the “social cost of carbon.” Also, based on the scientific nature of GHGs and the economic principles discussed above, EPA recommends consideration of estimates of the global marginal benefit of a reduction in GHGs, in addition to domestic estimates. Global estimates more fully capture the costs to society of GHG emissions, and ranges of estimates are appropriate given the uncertainties associated with modeling climate change impacts. Both global and domestic estimates provide relevant and meaningful information that could be useful to decision-makers and the public.

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[19] Marginal benefit estimates are very sensitive to the baseline socioeconomic and emissions baseline projections.

Some have posited that domestic marginal benefits are all that should be considered for domestic GHG policies.[20] Typically, because benefits and costs for most EPA policies are predominantly domestic, EPA focuses on benefits that accrue to the U.S. population when quantifying the impacts of regulations. However, as discussed above, domestic estimates do not account for the international externalities associated with US emissions. Furthermore, OMB's Circular A-4 specifically allows for consideration of international effects.[21] The use of domestic estimates alone implies that: (a) Americans do not value international damages caused by U.S. emissions (i.e., a willingness to pay of zero for avoiding international damages), and (b) international impacts will have no affect on domestic interests (e.g., risks to U.S. national security or the U.S. economy from potential disruptions in other nations). In addition, it follows from the economics and science points discussed previously, that actions based on current domestic direct benefit estimates (i.e., that exclude indirect benefits of avoiding adverse impacts in foreign countries) are not likely to significantly alter climate.

Based on these considerations, EPA developed ranges of both global and domestic marginal benefits estimates.[22] However, it is important to note at the outset that the estimates are incomplete since current methods are only able to reflect a partial accounting of the climate change impacts identified by the IPCC (discussed more below). Also, as noted above, domestic estimates omit potential impacts on the United States (e.g., economic or national security impacts) resulting from climate change impacts in other countries. Specifically, EPA developed ranges of estimates from a meta-analysis of global estimates in the peer reviewed literature, as well as a consistent set of U.S. and global estimate ranges with a single model—FUND (the "Climate Framework for Uncertainty, Negotiation, and Distribution" integrated assessment model].[23] The latter set

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[20] Recently, the National Highway Traffic Safety Administration (NHTSA) proposed new average fuel economy standards for passenger cars and light trucks that considered domestic marginal benefit estimates for carbon dioxide reductions. NHTSA wrote: "In order to be consistent with NHTSA's use of exclusively domestic costs and benefits in prior CAFE rulemakings, the appropriate value to be placed on changes in climate damages caused by carbon emissions should be one that reflects the change in damages to the United States alone. Accordingly, NHTSA notes that the value for the benefits of reducing CO_2 emissions might be restricted to the fraction of those benefits that are likely to be experienced within the United States" (p200). NHTSA's proposed standard is based on a value of \$7/tCO_2 in 2011 (2006\$), about \$6/tCO_2 in 2007 given NHTSA's assumed growth rate. They also performed sensitivity analyses with a range of \$0 to \$14/tCO_2 (approximately \$0 to \$13/tCO_2 in 2007). See section V.A.7.l.(iii) "Economic value of reductions in CO2 emissions", p. 24413 of Vol. 73 of the Federal Registry. Department of Transportation, National Highway Traffic Safety Administration, 49 CFR Parts 523, 531, 533, 534, 536 and 537, [Docket No. NHTSA-2008 -0089], RIN 2127-AK29, Average Fuel Economy Standards: Passenger Cars and Light Trucks, Model Years 2011-2015, http://www.regulations.gov/fdmspublic/component/main?main=DocumentDetail&o=0900006480541adc. EPA provided comments on May 3, 2008 and April 15, 2008 on the drafts of NHTSA's proposed rule, which included many of the issues discussed here.

[21] US OMB (2003), page 15. OMB notes: "Where you choose to evaluate a regulation that is likely to have effects beyond the borders of the United States, these effects should be reported separately."

[22] This was the approach taken by EPA for the analysis associated with EO 13432.

[23] FUND is a spatially and temporally consistent framework – across regions of the world (e.g., U.S., China), impacts sectors, and time. FUND explicitly models impacts sectors in 16 global regions. The impacts sectors are listed in Table 2. There are few models in the world capable of providing consistent global and regional marginal benefits estimates. FUND has produced recent global marginal benefits in the peer reviewed literature (e.g., Guo et al., 2006.)

of estimates was developed because the peer reviewed literature does not currently provide regional (i.e., at the U.S. or China level) marginal benefits estimates, and we believed that it was important to have a consistent set of regional and global estimates (i.e., with a consistent methodology and set of assumptions). The estimates are presented in Table 1. EPA considers the meta analysis results to be more robust than the single model estimates because the meta results reflect uncertainties in both models and assumptions, as well as being based on peer reviewed estimates and a peer reviewed approach. Furthermore, EPA considers the FUND estimates to be extremely preliminary. Given the pace of events, we have not had time for model development and peer review with the FUND model. We are now reviewing and assessing the FUND estimates and modeling relative to the latest research. Among other things, we are evaluating several factors not currently captured (discussed below). While the FUND estimates are very preliminary, we believe it is useful to make them available given the on-going public dialogue on climate policy.

Table 1 provides ranges of estimates by year of emissions change and for different discount rates. The low, central, and high are the 5th percentile, mean, and 95th percentile for the meta-analysis, while for FUND, they are the lowest, weighted average, and highest values from sensitivity analysis (discussed in more detail below).[24] The estimates increase over time since future emissions are expected to produce larger incremental damages as physical and economic systems become more stressed as the magnitude of climate change increases.[25] Note that, except for illustrative purposes, the marginal benefits estimates in the peer reviewed literature do not use discount rates as high as 7%.

Table 1: Marginal GHG Benefits Estimates for Discount Rates of approximately 2%, 3%, and 7% and Year of Emissions Change (all values are reported in 2006$/tCO$_2$)

		~ 2%			~ 3%			~ 7%		
		Low	Central	High	Low	Central	High	Low	Central	High
Meta global	2007	-3	68	159	-4	40	106	n/a	n/a	n/a
	2017	-2	91	213	-3	53	142	n/a	n/a	n/a
	2022	-2	105	247	-2	62	165	n/a	n/a	n/a
	2030	-1	134	314	-2	78	209	n/a	n/a	n/a
	2040	-1	179	421	-1	105	281	n/a	n/a	n/a
FUND global	2007	-6	88	695	-6	17	132	-3	-1	5
	2017	-4	118	934	-4	23	178	-2	-1	7
	2022	-4	136	1083	-4	26	206	-2	-1	9
	2030	-3	173	1372	-3	33	261	-1	0	11
	2040	-2	232	1843	-2	44	351	-1	0	15
FUND domestic	2007	0	4	16	0	1	5	0	0	0
	2017	0*	6	22	0*	1	7	0*	0*	0*
	2022	0*	7	26	0*	2	9	0*	0*	0*
	2030	0*	9	32	0*	2	11	0*	0*	0*
	2040	0*	12	44	0*	3	15	0*	0*	0*

* These estimates, if explicitly estimated, may be greater than zero, especially in later years. They are currently reported as zero because the explicit estimates for an earlier year were zero and were grown at 3% per year. However,

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[24] Means are presented because, as a central statistic, they better represent the skewed shape of these distributions compared to medians. The distribution of estimates in all cases—meta and FUND—are skewed to the right.

[25] The IPCC suggests an increase of 2 to 4% per year (p. 813, IPCC WGII, 2007). For Table 1, we assumed the estimates increased at 3% per year.

we do not anticipate that the explicit estimates for these later years would be significantly above zero given the magnitude of the current central estimates for discount rates of 2% and 3% and the effect of the high discount rate in the case of 7%.

The meta analysis ranges were developed by refining the meta analyses of Tol (2005) and Tol (2007).[26] Tol (2005) was a main reference in Chapter 20 of the IPCC Working Group II's Fourth Assessment Report (IPCC WGII, 2007). Tol (2007) is an update of Tol (2005) that includes additional and more recent estimates. The EPA meta-analysis limited consideration to estimates generated by more recent peer reviewed studies (i.e., published after 1995). In addition, we only considered regional aggregations based on simple summations (i.e., without "equity weighting") and intergenerational consumption discount rates of approximately 2% and 3%.[27] Discount rates of 2% and 3% are consistent with EPA and OMB guidance on intergenerational discount rates (EPA, 2000; OMB, 2003). The estimated distributions of the meta global estimates are right skewed with long right tails, which is consistent with characterizations of low probability high impact damages.[28]

The consistent domestic and global estimates were developed using FUND. The ranges were generated from sensitivity analysis where we varied assumptions with respect to climate sensitivity (1.5 to 6.0 degrees Celsius),[29] the socio-economic and emissions baseline scenarios (the FUND default baseline and three baselines from the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios, SRES)[30], and the consumption discount rates of approximately 2%, 3%, and 7%.[31] Furthermore, the model was calibrated to the EPA value of a statistical life of $7.4 million (in 2006 real dollars).[32] The FUND global estimates are the sum of the regional estimates within FUND, and the regional estimates are the sum of the sectoral effects within each region. The FUND global and domestic central values in Table 1 are weighted averages of the FUND estimates from the sensitivity analysis.[33]

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[26] Tol (2007) has been published on-line with peer review comments (http://www.economics-ejournal.org/economics/discussionpapers/2007-44).

[27] Following Tol (2007), we estimated probability density functions using a Fisher-Tippett distribution since the sample was right-skewed with a thick right tail.

[28] E.g., Webster et al. (2003). Also, see Weitzman, M., 2007 and Weitzman, M., 2008

[29] In IPCC reports, equilibrium climate sensitivity refers to the equilibrium change in the annual mean global surface temperature following a doubling of the atmospheric equivalent carbon dioxide concentration. The IPCC states that climate sensitivity is "likely" to be in the range of 2°C to 4.5°C and described 3°C as a "best estimate", which is the mode (or most frequent) value. The IPCC goes on to note that climate sensitivity is "very unlikely" to be less than 1.5°C and "values substantially higher than 4.5°C cannot be excluded." IPCC WGI (2007).

[30] The IMAGE model SRES baseline data was used for the A1b, A2, and B2 scenarios (IPCC, 2000. *Special Report on Emissions Scenarios*. A special report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge).

[31] The EPA guidance on intergenerational discounting states that "[e]conomic analyses should present a sensitivity analysis of alternative discount rates, including discounting at two to three percent and seven percent as in the intra-generational case, as well as scenarios using rates in the interval one-half to three percent as prescribed by optimal growth models." (US EPA, 2000)

[32] This number may be updated to be consistent with recent EPA regulatory impact analyses that has used a value of $6.4 million (in 2006 real dollars).

[33] The weighted averages are based on a probability distribution function for climate sensitivity derived from the IPCC WGI (2007) Chapter 10 and a uniform distribution for the socioeconomic baselines.

The broad range of estimates in Table 1 reflects some of the uncertainty associated with estimating monetized marginal benefits of climate change.[34] The estimates are very sensitive to assumptions. For instance, higher marginal damages from GHG emissions are associated with higher climate sensitivities, lower economic growth per capita globally and regionally, and lower discount rates. The meta analysis range reflects differences in these assumptions as well as differences in the modeling of changes in climate and impacts considered and how they were modeled. As noted, EPA considers the meta analysis results to be more robust.

Emissions reductions are expected to have a direct benefit for current and future U.S. populations as well as much larger benefits for the rest of the world (in the aggregate). The ratio of domestic to global benefits will vary with assumptions, such as relative economic growth and severity of impacts, climate responsiveness, and discount rate.[35] Note that the long-run and intergenerational implications of GHG emissions are evident in the significant difference in the estimates across discount rates in Table 1. There are substantial long-run benefits (beyond the next two decades to over 100 years) and some near-term benefits as well as negative effects (e.g., changes in agricultural productivity and heating demand). High discount rates give less weight to the distant benefits in the net present value calculations, and more weight to near-term effects. In general, the distribution of benefits across regions, impact categories, and time is far from uniform. However, it is difficult to see and evaluate these dimensions in the aggregate estimates in Table 1. In the future, it will be helpful to disaggregate the estimates across all three of these dimensions.

For comparison, Tol (2005) derives two sets of statistics from the peer reviewed marginal benefits estimates considered: “quality weighted” and “composite probability density function,” where the later is an estimated distribution for the sample of estimates. The quality weighted mean is \$12/tCO2 (\$43 per tonne carbon, tC) with a standard deviation of \$23/tCO2 (\$83/tC). The composite probability density function mean is \$14/tCO_2 (\$50/tC) with 95th percentile of \$67/tCO_2 (\$245/tC). These estimates are in 1995 real dollars and are relevant for changes in carbon dioxide emissions circa 1995.[36] Applying a damages growth rate of 3%, the adjusted quality weighted statistics for changes in carbon dioxide emissions in 2007 (in 2006 dollars) are mean \$21/tCO_2 with standard deviation \$41/tCO_2, while the adjusted composite probability density function mean is \$25/tCO_2 with 95th percentile \$121/tCO_2.

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[34] Because of the global nature of CO_2 and other greenhouse gases, estimating the marginal benefits requires a global modeling framework with consistent integrated socioeconomics, emissions, climate change, and impacts. Given uncertainties in socio-economic futures (e.g., population growth, economic growth, and technology availability and diffusion), corresponding GHG emissions, climate responses to emissions changes, and the bio-physical and economic impacts associated with changes in climate, the quantified (physical and monetized) estimates of climate change impacts are inherently uncertain.

[35] For instance, with a 3% discount rate, the US benefit is 6% of the global benefit for the “central” (mean) FUND results; while, for the corresponding “high” estimates associated with a higher climate sensitivity and lower global economic growth, the US benefit is 4% of the global benefit.

[36] Information obtained via personal communication with Richard Tol.

Compared to Table 1, the adjusted Tol (2005) means are lower, and the 95th percentile of the composite probability density function is higher. The differences can be attributed to the remaining differences in the samples considered. First, we used the updated Tol (2007) meta analysis as the foundation for the EPA meta analysis estimates. Tol (2007) updated Tol (2005) to include a more complete and current list of estimates. The Tol (2005) peer review statistics include estimates with all discount rates, above and below 3% consumption discount rates. The Tol (2005) peer review statistics include equity weighted estimates, which give greater weight to impacts in poorer countries. Finally, the Tol (2005) peer review statistics include studies published before and after 1995. These differences do not uniformly suggest that the EPA estimates should be higher or lower than Tol (2005). However, as seen in Table 1, higher discount rates will have a significant effect on estimates and Tol's inclusion of estimates with discount rates above 3% causes the Tol (2005) statistics to be lower than the EPA estimates.

4,2 Discussion and application

In addition to the large quantified uncertainties evident in the estimates in Table 1, there are significant omitted impacts categories. The IPCC WGII (2007) states that current estimates are "very likely" to be underestimated because they do not include significant impacts that have yet to be monetized.[37] Current estimates do not capture many of the main reasons for concern about climate change, i.e., non-market damages, the effects of climate variability, risks of potential extreme weather (e.g., droughts, heavy rains and wind), socially contingent effects (such as violent conflict),[38] and potential long-term catastrophic events. Underestimation is considered even more likely when one considers that the current trajectory for GHG emissions is higher than typically modeled, which combined with current regional population and income trajectories that are more asymmetric than typically modeled, imply greater climate change and vulnerability to climate change.

In Table 2, we provide a list of the impacts currently included in the FUND model, and an initial, partial list of impacts that are currently not included in FUND. FUND is one of the main models used in generating marginal benefits estimates, and is fairly representative. A key challenge for many impacts sectors is data limitations (primarily physical data). Note that most of the omitted impacts are likely to lead to additional benefits in response to reductions in GHG emissions, including international impacts that could affect domestic benefits (e.g., potential impact feedbacks to the United States, U.S. concern for international impacts, and international participation). EPA plans to conduct a comprehensive review of these categories.

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[37] IPCC WGII, 2007. In the IPCC report, "the following terms [were] used to indicate the assessed likelihood, using expert judgment, of an outcome or a result: Virtually certain > 99% probability of occurrence, Extremely likely > 95%, Very likely > 90%, Likely > 66%, More likely than not > 50%, Unlikely < 33%, Very unlikely < 10%, Extremely unlikely < 5%."

[38] For example, increased pressure on resources (e.g., water, land, and food) may increase potential for armed conflict and other major social changes, which would have additional costs associated with them. Similarly, a humanitarian crisis associated with extreme weather would imply additional costs.

Furthermore, the current marginal benefits estimates in the literature are generally deterministic in that they do not account for changes in the likelihood of potential impacts associated with reductions in CO_2 and other GHG emissions. As discussed previously, Weitzman and others have noted that deterministic approaches do not quantify the value of changes in uncertainty and risk and may lead to underestimation of the benefits from undertaking action. Furthermore, Weitzman has also criticized previous analyses for their failure to consider high-impact, low-probability climate conditions. In the future, EPA will be evaluating alternatives for quantifying changes in uncertainty and reductions in risk, including those associated with potential high-impact, low-probability outcomes.

When applying the marginal benefits estimates, it is prudent to consider the science of GHGs, the relevant economic principles, and the state of the art for estimating marginal benefits. For instance, the estimates in Table 1 are not estimates of economically "optimal" marginal benefits (i.e., they are not associated with an emissions reduction level where marginal benefits equal marginal costs). These estimates are only relevant for incremental policies relative to the projected baselines (that do not reflect potential future climate policies). Furthermore, because current marginal benefits estimates are incomplete and highly uncertain (with many uncertainties outside of observed variability), we cannot use them to identify an *economically optimal (or economically efficient)* standard, even for incremental changes in global GHG emissions. In general, the uncertainties and omissions of important impacts categories poses problems for benefit-cost criteria, including basic application of positive net benefit criteria (i.e., benefit-cost ratios greater than one). As a result, it is important to recognize the deficiencies and

Table 2: Lists of Impacts Modeled and Omitted from Current FUND Modeling

Impacts currently modeled in FUND	**Examples of impacts omitted from current FUND modeling***
• Agricultural production • Forestry production • Water resources • Energy consumption for space cooling & heating • Sea level rise dry land loss, wetland loss, and coastal protection costs • Forced migration due to dry land loss • Changes in human health (mortality, morbidity) associated with diarrhea incidence, vector-borne diseases, cardiovascular disorders, and respiratory disorders • Hurricane damage • Loss of ecosystems/biodiversity	• Catastrophic events (e.g., Antarctic ice sheet collapse) • Risks from extreme weather (e.g., death, disease and economic damage from droughts, floods, and fires) • Air quality degradation (e.g., increased ozone effects including premature mortality, forest damage) • Increased infrastructure costs (e.g., water management systems, roads, bridges) • Increased insurance costs • Social and political unrest abroad that affects U.S. national security • Damage to foreign economies that affects the U.S. economy • Domestic valuation of international impacts • Costs from uncertainty and changes in risk • Arctic sea ice melt and global transportation & trade

* A comprehensive review of included and omitted impact categories in current marginal benefits modeling is planned.

consider factors beyond the monetized benefits when developing standards that are a function of the value of GHG effects.

Global marginal benefit estimates internalize a portion of the global and intergenerational externalities of reducing a unit of emissions. While the global marginal benefits estimates in Table 1 are not comprehensive or economically optimal, they can help guide policies towards more efficient levels of provision of the public good.

In the future, we will be developing and updating the marginal benefits estimates as possible based on the latest research and peer reviewed estimates. To improve upon the estimates, we hope to evaluate several factors not currently captured in the current estimates. For example, we will attempt to quantify additional impact categories and provide a qualitative evaluation of the implications of what is not monetized. We also plan to conduct an uncertainty analysis, consider complementary bottom-up analyses, and develop estimates of the marginal benefits associated with non-CO_2 GHGs (e.g., CH_4, N_2O, and HFC-134a).[39]

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[39] Due to differences in atmospheric lifetime and radiative forcing, non-CO_2 GHGs have different climate implications and therefore different marginal climate impacts. As a result, the marginal benefit values of non-CO_2 GHG reductions and their growth rates over time will not be the same as the marginal benefits of CO_2 emissions reductions (IPCC WGII, 2007). It is important to note that CO_2 equivalent measures of non-

4.3 Estimating Total Monetized GHG Benefits

For policies expected to have an incremental affect on global GHG emissions, estimating total monetized GHG benefits is straightforward. Annual marginal benefits and emissions reductions can be estimated separately and simply multiplied together, i.e., Total monetized benefits in year t = (Marginal benefit per metric ton in year t) x (Emissions reduction in year t).[40] For each period year, a range of total benefits estimates would be based on the range of marginal benefit estimates (and emissions reduction estimates, if there is more than one estimate in that year). For non-incremental changes in global GHG emissions, the projected changes in climate change impacts are expected to be sensitive to interactions between sectors and regions, biophysical and economic feedbacks, and socioeconomic transformations, as well as non-linearities in impacts; thereby, calling for simultaneous integrated estimation of total GHG mitigation and changes in potential impacts.

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CO_2 GHGs based on 100-year global warming potentials do not accurately capture the radiative forcing effects of each non-CO_2 GHG.

[40] Ideally, given the differences in the climate implications of each GHG, emissions reductions should be separated by gas and gas specific marginal benefits estimates should be used.

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