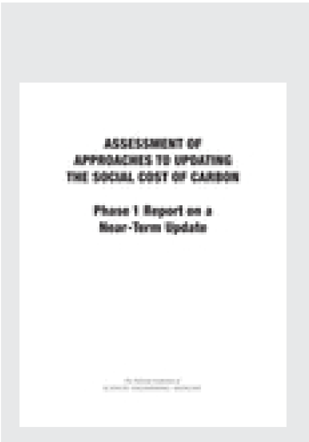

Assessment of Approaches to Updating the Social Cost of Carbon: Phase 1 Report on a Near-Term Update

DETAILS

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AUTHORS

Committee on Assessing Approaches to Updating the Social Cost of Carbon; Board on Environmental Change and Society; Division of Behavioral and Social Sciences and Education; National Academies of Sciences, Engineering, and Medicine

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Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Academies of Sciences, Engineering, and Medicine's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We thank the following individuals for their participation in their review of this report:

Kenneth J. Arrow, Department of Economics, Stanford University;
James (Jae) Edmonds, Joint Global Change Research Institute, Pacific Northwest National Laboratory;
Peter Kelemen, Department of Earth and Environmental Sciences, Columbia University and Lamont-Doherty Earth Observatory;
Bryan K. Mignone, Corporate Strategic Research, ExxonMobil Research and Engineering Company;
Elisabeth Moyer, Department of Geophysical Sciences, University of Chicago;
William D. Nordhaus, Department of Economics, Yale University; and
David Weisbach, The University of Chicago Law School and The Computation Institute, University of Chicago and Argonne National Laboratories.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions nor did they see the final draft of the report before its release. The review of this report was overseen by Elisabeth M. Drake, Massachusetts Institute of Technology, appointed by the Division of Behavioral and Social Sciences and Education, and Charles F. Manski, Northwestern University, appointed by the Report Review Committee, who were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

Acronyms

AR4	IPCC's Fourth Assessment Report
AR5	IPCC's Fifth Assessment Report
CH_4	Methane
CMIP3	Coupled Model Intercomparison Project Phase 3
CMIP5	Coupled Model Intercomparison Project Phase 5
CO_2	Carbon dioxide
DICE	Dynamic Integrated Climate-Economy Model
ECS	Equilibrium climate sensitivity
EgC	Exagram of carbon, 1 trillion tons of fossil carbon
EMF 22	Energy Modeling Forum's 22nd study
FUND	Climate Framework for Uncertainty, Negotiation and Distribution
Gt	Gigaton, 1,000,000,000 tons
IAM	Integrated assessment model
IPCC	Intergovernmental Panel on Climate Change
IPT	Initial pulse-adjustment timescale
IWG	Interagency Working Group on the Social Cost of Carbon
N_2O	Nitrous oxide
OMB	Office of Budget and Management
PAGE	Policy Analysis of the Greenhouse Effect
PETM	Paleocene-Eocene Thermal Maximum (in Figure 3-1)
ppm	Parts per million
RCP/ECP	Representative concentration pathway/extended concentration pathway
SCC	Social cost of carbon
SF_6	Sulfur hexafluoride
TCR	Transient climate response
TCRE	Transient climate response to cumulative carbon emissions
Tt C	Teraton of carbon, 1 trillion tons of fossil carbon
USG1	U.S. Government 1 (a designation for one of the five socioeconomic scenarios used in the IAMs)
USG2	U.S. Government 2 (a designation for one of the five socioeconomic scenarios used in the IAMs)
USG5	U.S. Government 5 (a designation for one of the five socioeconomic scenarios used in the IAMs)
W/m^2	Watts per square meter

Executive Summary

The social cost of carbon (SCC) for a given year is an estimate, in dollars, of the present discounted value of the damage caused by a 1-metric ton increase in carbon dioxide (CO_2) emissions into the atmosphere in that year or, equivalently, the benefits of reducing CO_2 emissions by the same amount in that year. The SCC is intended to provide a comprehensive measure of the monetized value of the net damages from global climate change that results from an additional unit of CO_2, including, but not limited to, changes in net agricultural productivity, energy use, human health effects, and property damages from increased flood risk. Federal agencies use the SCC to value the CO_2 emissions impacts of various regulations, including emission and fuel economy standards for vehicles; emission standards for industrial manufacturing, power plants, and solid waste incineration; and appliance energy efficiency standards.

The Interagency Working Group on the Social Cost of Carbon (IWG) developed a methodology for estimating the SCC and applied that methodology to produce estimates that government agencies use in regulatory impact analyses under Executive Order 12866. The IWG requested this Academies interim report to determine if a near-term update to the SCC is warranted, with specific questions pertaining to the representation of the equilibrium response of the climate system in the integrated assessment models used by the SCC modeling structure, as well as the presentation of uncertainty of the SCC estimates. This interim report is the first of two reports requested by the IWG: the second (Phase 2) report will examine potential approaches for a more comprehensive update to the SCC estimates.

The committee concludes that there would not be sufficient benefit of modifying the estimates to merit a near-term update that would be based on revising a specific parameter in the existing framework used by the IWG to reflect the most recent scientific consensus on how global mean temperature is, in equilibrium, affected by CO_2 emissions. Furthermore, the committee does not recommend changing the distributional form used to capture uncertainty in the equilibrium CO_2 emissions-temperature relationship. Rather than simply updating the distribution used for equilibrium climate sensitivity—the link that translates CO_2 emissions to global temperature change—in the current framework, the IWG could undertake efforts toward the adoption or development of a common representation of the relationship between CO_2 emissions and global mean surface temperature change, its uncertainty, and its profile over time. The committee outlines specific diagnostic criteria that can be used to assess whether such a module is consistent with the best available science.

Further, the committee recommends that the IWG provide guidance in their technical support documents about how SCC uncertainty should be represented and discussed in individual regulatory impact analyses that use the SCC. The committee recommends that each update of the SCC include a section in the technical support document that discusses the various types of uncertainty in the overall SCC estimation approach, addresses how different models used in SCC estimation capture uncertainty, and discusses uncertainty that is not captured in the estimates. In addition, the committee notes that it is important to separate the effects of the discount rate on the SCC from the effects of other sources of variability. Finally, the committee recommends that the IWG provide symmetric treatment of both low and high values from the frequency distribution of SCC estimates conditional on each discount rate.

The committee also reminds readers that it will be exploring these and other broader issues further in Phase 2 of this study; the committee may offer further discussion of these issues in its Phase 2 report including the modeling of the climate system and the representation of uncertainty in the estimation of the SCC.

1
Introduction

The social cost of carbon (SCC) for a given year is an estimate, in dollars, of the present discounted value of the damage caused by a 1-metric ton increase in CO_2 emissions into the atmosphere in that year or, equivalently, the benefits of reducing CO_2 emissions by the same amount in that given year.[1] The SCC is intended to provide a comprehensive measure of the monetized value of the net damages from global climate change from an additional unit of CO_2, including, but not limited to, changes in net agricultural productivity, energy use, human health effects, and property damages from increased flood risk.[2] Federal agencies use the SCC to value the CO_2 emissions impacts of various policies including emission and fuel economy standards for vehicles, regulations of industrial air pollutants from industrial manufacturing, emission standards for power plants and solid waste incineration, and appliance energy efficiency standards.

HISTORY AND DEVELOPMENT OF THE SCC

The effort to incorporate the SCC into regulatory decision making started during the latter part of the George W. Bush Administration. Prior to 2008, changes in CO_2 emissions were not valued in the cost-benefit analysis required when establishing federal rules and regulations (U.S. Government Accountability Office, 2014, p. 5). After a 2008 court ruling[3] that required incorporation of the benefits of CO_2 emissions reductions in every regulatory impact analysis, federal agencies began using a variety of methodologies for determining a dollar value for the SCC. In an effort to standardize SCC estimates across the federal government, in 2009 the Obama Administration assembled the Interagency Working Group on the Social Cost of Carbon (IWG) of technical experts from across the government to develop a single set of estimates.[4] Interim values for the SCC from the IWG were first used in a regulatory impact analysis for an August 2009 Department of Energy energy efficiency standard for beverage vending machines (74 *Federal Register* 44914). The SCC has since been used in dozens of regulatory actions (U.S. Government Accountability Office, 2014, App. I). For example, the March 2010 *Energy Conservation Program: Energy Conservation Standards for Small Electric Motors Final Rule*[5] used the SCC to monetize its global climate impacts.

Following the establishment of interim values for the SCC, the IWG undertook a more in-depth process that produced a February 2010 Technical Support Document with a more fully

[1] In this report, we present all values of the SCC as the cost per metric ton of CO_2 emissions.

[2] Here, and throughout this report, "damage" is taken to represent the net effects of both negative and positive economic outcomes of climate change.

[3] *Center for Biological Diversity v. National Highway Traffic Safety Administration,* U.S. Court of Appeals, Ninth Circuit, 538 F.3d 1172 (9th Cir. 2008).

[4] The IWG, which operates under the U.S. Global Change Committee, is cochaired by the Council of Economic Advisors and the Office of Management and Budget; the other members are the Council on Environmental Quality, the Domestic Policy Council, the Department of Agriculture, the Department of Commerce, the Department of Energy, the Department of Transportation, the Environmental Protection Agency, the National Economic Council, the Office of Science and Technology Policy, and the Department of the Treasury.

[5] EERE–2007–BT–STD–0007, 75 *Federal Register* 10873.

developed methodology and a resulting set of four SCC estimates for use by government agencies. The estimates were developed employing the three most widely cited integrated assessment models (IAMs) that are capable of estimating the SCC, which this report refers to as "SCC-IAMs." Although the three SCC-IAMs were not developed solely to estimate the SCC, they are among the very few models that calculate net economic damages from CO_2 emissions. Since there are many IAMs in use in the climate change research community for multiple purposes, this report refers to these three models specifically as SCC-IAMs.[6]

The IWG retained most of the SCC-IAMs developers' default assumptions for the parameters and functional forms in the models, but with some important exceptions, and also a harmonized approach to discounting the results in future time periods across the models. The two exceptions are that the IWG used a single probability distribution for the equilibrium climate sensitivity (ECS)[7] parameter for all models, as well as a common set of five future socioeconomic and emissions scenarios. In addition, three constant discount rates were used for each SCC-IAM. The analysis resulted in 45 sets of estimates (three IAMs, five socioeconomic-emissions scenarios, one ECS distribution, and three discount rates) for the SCC for a given year, with each set comprising 10,000 estimates drawn on the basis of the uncertain variables in the models. The IWG summarized the results into an average value for each discount rate, plus a fourth value, selected at the 95th percentile for a 3 percent discount rate, intended to represent higher-than-expected impacts from temperature change farther out in the tail of the SCC estimates.

Motivation for the Study

There are significant challenges to estimating a dollar value that reflects all the physical, human, ecological, and economic impacts of climate change. Recognizing that the models and scientific data underlying the SCC estimates evolve and improve over time, the federal government made a commitment to provide regular updates to the estimates. For example, the IWG updated SCC estimates in May 2013 to take into account a variety of model-specific updates in each of the three SCC-IAMs.[8]

The IWG requested this National Academies of Sciences, Engineering, and Medicine study to assist future revisions of the SCC in two important ways. First, it requested that this study provide government agencies that are part of the IWG with an assessment of the merits and challenges of a limited near-term update to the SCC. Specifically, it requested that the committee consider whether there is sufficient benefit to conducting a limited near-term update to the SCC in light of ECS updates in the Fifth Assessment Report (AR5) of Working Group 1 of the Intergovernmental Panel on Climate Change (IPCC); whether a different distributional form should be used for the ECS; and whether the IWG should adopt changes in its approaches for

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[6]There are many types of IAMs, which vary significantly in structure, resolution, computational algorithm, and application. In comparison with most other IAMs, the three SCC-IAMs used by the IWG, Dynamic Integrated Climate-Economy Model, Framework for Uncertainty, Negotiation and Distribution, and Policy Analysis of the Greenhouse Effect are specialized in their focus on modeling aggregate global climate damages and their highly aggregated economic and energy system representations, rather than being focused on potential economic, energy, and land system development and transformation. We note, however, that these models were not designed solely to estimate the SCC.

[7]ECS measures the long-term response of global mean temperature to a fixed forcing, conventionally taken as an instantaneous doubling of CO_2 concentrations from their preindustrial levels; see Chapter 3.

[8]In November 2013 and July 2015, the IWG also revised the estimates slightly to account for minor technical corrections.

enhancing the qualitative characterization of limitations and uncertainties in SCC estimates to increase their transparency for use in regulatory impact analyses.

Second, the IWG requested that the committee consider the merits and challenges of a comprehensive update of the SCC to ensure that the estimates reflect the best available science. Specifically, it requested that the committee review the available science to determine its applicability for the choice of IAMs and damage functions and examine issues related to climate science modeling assumptions, socioeconomic and emissions scenarios, the presentation of uncertainty, and discounting. The full statement of task is in Box 1-1.

Accordingly, the committee will recommend approaches that warrant consideration in future updates of the SCC estimates, as well as recommendations for research to advance the science in areas that are particularly useful for estimating the SCC. The committee will examine the merits and challenges of potential approaches for both a near-term limited update and longer-term comprehensive updates to ensure that the SCC estimates reflect the best available science and methods. As such, the study will be conducted in two phases and will result in two reports. This interim report focuses on near-term updates to the SCC estimates, Phase 1 of the study, and is narrowly scoped so that a consensus report could be produced in the short time line required (within 6 months). Phase 2 allows for broader consideration of the SCC.

BOX 1-1
Statement of Task

An ad hoc multidisciplinary committee will be appointed to inform future revisions to estimates of the social cost of carbon (SCC) developed and used by the federal government. The committee will examine the merits and challenges of potential approaches for both a near-term limited update and longer-term comprehensive updates to ensure that the SCC estimates continue to reflect the best available science and methods. The study will be conducted in two phases and will result in two reports.

Phase 1.

In Phase 1, the committee will assess the technical merits and challenges of a narrowly focused update to the SCC estimates and make a recommendation on whether to conduct an update of the SCC estimates prior to recommendations related to a more comprehensive update based on its review of the science related to the topics covered in the second phase. Specifically, the committee will consider whether an update is warranted based on the following:

1. Updating the probability distribution for the ECS to reflect the recent Intergovernmental Panel on Climate Change (IPCC) consensus statement in the Fifth Assessment Report of the IPCC, rather than the current calibration used in the SCC estimates, which were based on the most authoritative scientific consensus statement available at the time (the 2007 Fourth IPCC Assessment).
2. Recalibrating the distributional forms for the ECS by methods other than the currently used Roe and Baker (2007) distribution.
3. Enhancing the qualitative characterization of uncertainties associated with the current SCC estimates in the short term to increase the transparency associated with using these estimates in regulatory impact analyses. Noting that as part of a potential comprehensive update Part 2 of the charge requests information regarding the opportunity for a more comprehensive, and possibly more formal or quantitative, treatment of uncertainty.

The Phase 1 report will be an interim letter report to be completed in 6 months.

Phase 2.

In Phase 2, which represents the bulk of the statement of task, the committee will examine potential approaches, along with their relative merits and challenges, for a more comprehensive update to the SCC estimates to ensure the estimates continue to reflect the best available science. The committee will be asked to consider issues related to

1. an assessment of the available science and how it would impact the choice of integrated assessment models and damage functions,
2. climate science modeling assumptions,
3. socioeconomic and emissions scenarios,
4. presentation of uncertainty, and
5. discounting.

Within these areas, the committee will make recommendations on potential approaches that warrant consideration in future updates of the SCC estimates, as well as research recommendations based on their review that would advance the science in areas that are particularly useful for estimating the SCC.

Strategy to Address the Study Charge

This study was carried out by a committee of experts appointed by the president of the Academies. The committee consists of 13 members, with the assistance of a technical consultant and study staff. Committee expertise spans the issues relevant to the study task: environmental economics, climate science, energy economics, integrated assessment modeling, decision science, climate impacts, statistical modeling, and public policy and regulation. In composing the committee, care was taken to ensure that the membership possessed the necessary balance between research and practice by including academic scientists and other professionals, that members have the relevant disciplinary expertise, and to ensure there are no current connections that might constitute a conflict of interest with the Department of Energy, the Environmental Protection Agency, or other regulatory agency members of the IWG. The committee cochairs are experts in the fields of environmental and energy economics with demonstrated leadership capabilities. Biographical sketches of the committee members and staff are provided in Appendix A.

To address the Phase 1 task, the committee held one open meeting to receive information from federal agency staff to understand and explore its study charge; see Appendix B for the agenda. Closed sessions at the initial meeting and two subsequent meetings were held to refine and finalize the committee's findings and recommendations. The main body of the report addresses the Phase 1 charge questions.

CRITERIA AND CHALLENGES FOR A NEAR-TERM UPDATE

The committee considered a number of criteria for evaluating the merits and challenges of a near-term update to ECS assumptions within the framework for estimating the SCC. A "near-term update" was understood by the committee to be actions that government staff could undertake in less than 1 year. Specifically, the committee considered five main issues:

1. **Accuracy and characterization of uncertainty of climate system modeling.** If the ECS is updated within the existing SCC modeling framework to reflect the current scientific consensus as represented by the AR5, will it necessarily improve the representation of the response of temperature change to emissions, relative to more complete, state-of-the-art models of the climate system? Both the accuracy and characterization of uncertainty of the emissions-temperature relationship over time are important aspects of that representation.
2. **Overall SCC reliability.** Would a near-term improvement to the representation of ECS be likely to substantially improve the overall SCC estimate, given other elements of the IWG SCC framework that may also warrant improvement?
3. **Alternative options for climate system representation.** Are there near- to mid-term options—in addition to simply adjusting the ECS within the current framework—for altering the representation of the emission-temperature response in the SCC framework? Would these options enhance the ability of the IWG to undertake future updates in a manner that is well connected to developments in the climate science community?
4. **Opportunity cost of near-term efforts in terms of potential longer-term improvements.** Would the value of any near-term update, in terms of improvement in the SCC, justify the opportunity costs of engaging in the effort, rather than focusing instead on longer-term improvements to the SCC? Would such a change, if implemented, be likely to have a substantial effect on the SCC, thereby potentially warranting the near-term investment of resources related to the development of revised SCC estimates?
5. **Consistency of Phase 1 with possible Phase 2 conclusions and recommendations.** Would any actions taken in response to Phase 1 recommendations likely be consistent with actions taken in response to possible Phase 2 recommendations?

The committee also considered specific technical details in their analysis as described in later chapters.

STRUCTURE OF THE REPORT

The rest of the report covers the topics addressed in Phase 1. Chapter 2 describes how the IWG constructed the SCC estimates and is intended to be accessible to all readers. Chapters 3 and 4 present the technical details that underlie the committee's conclusions and recommendations. Chapter 3 describes the role of the ECS in determining temperature changes and discusses several additional relevant climate metrics that reflect the state of the climate literature. Chapter 4 highlights differences in the way the SCC-IAMs represent the climate system. Chapter 5 then summarizes the conclusions from the previous chapters and provides recommendations for whether a limited, short-term update to the ECS distribution is warranted and on how the qualitative characterization of uncertainty can be improved.

Consideration of broader updates to the SCC—including economic damages and damage functions, socioeconomic scenarios, and discounting—are not addressed in this report. These topics will be addressed in Phase 2 of the study, along with further assessment of climate system modeling the treatment of uncertainty (see Box 1-1, above).

2
Modeling the Climate System within the Broader SCC Modeling Structure

This chapter reviews the current methodology used to calculate the social cost of carbon (SCC) to provide the context for the committee's analysis, conclusions, and recommendations. We focus in particular on the assumptions that differ among the SCC integrated assessment models (SSC-IAMs) and uncertainties in the modeling framework.

STEPS IN CONSTRUCTING THE SCC: OVERVIEW

In order to estimate the SCC, one needs to project both the sequence of future annual incremental changes in the climate and the resulting economic damages from a marginal increase in CO_2 emissions, and then convert the stream of incremental economic damages into a present value equivalent (i.e., the total dollar value at the time of emissions of the discounted stream of future damages).[9] Since the atmospheric impacts of CO_2 emissions are global and vary over time, this calculation is complex, and it requires a global model with a long time horizon. The approach taken by the Interagency Working Group on the Social Cost of Carbon (IWG) was to utilize damage valuations from the three SCC-IAMs, described in more detail below. The SCC-IAMs use the causal chain of modeling steps to project incremental changes in climate change and resulting economic damages; see Figure 2-1.

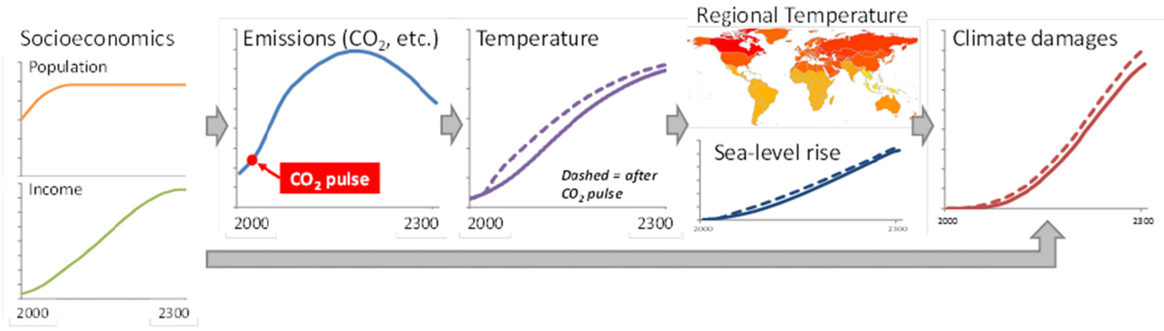

FIGURE 2-1 SCC modeling causal chain.
NOTE: Each figure in this chain represents a key element in the models used to produce estimates of the SCC with projections from one element flowing into the next element. Population and income projections are inputs to the derivation of projections for both emissions and climate damages.
SOURCE: Developed from Rose et al. (2014). Reprinted with permission.

[9] Damages from global climate change include, but are not limited to, changes in net agricultural productivity, energy use, human health effects, and property damages from increased flood risk.

Each model takes as inputs a projection of human population growth and of global or regional income, as well as emissions paths of global greenhouse gases.[10] A simple climate model component of each SCC-IAM translates the reference emissions trajectory into a reference global mean temperature trajectory and a reference trajectory of global mean sea level rise. In two of the models, regional average temperature trajectories are also derived from global mean temperature. Each model then uses one or multiple damage functions to translate temperature and sea level rise into economic damages or benefits. In the IWG analysis, global damages in the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) and Policy Analysis of the Greenhouse Effect (PAGE) are an equally weighted sum of regional damages (i.e., no equity weighting) (Interagency Working Group on the Social Cost of Carbon, 2010, p. 11).

In order to derive an SCC estimate, the impact of a CO_2 emissions pulse is calculated following the same causal chain: the CO_2 pulse is introduced in a particular year, creating a trajectory of temperature (global and regional), sea level rise, and climate damages. The difference between this damage trajectory (the dotted line in Figure 2-1, above) and the reference trajectory (the solid line) in each year is discounted to the present using annual discounting (a constant annual discount rate in the IWG application). The resulting value is an SCC estimate for the given set of assumptions used in the reference and perturbed scenarios.

There are several steps in the causal chain for each SCC-IAM that are worth highlighting because they are different across models and have notable implications for the ultimate calculation of an SCC estimate. We discuss these differences in more detail below, but flag them here:

- emissions can vary in terms of their coverage and time path;
- the reference and perturbed temperature trajectories depend on the way the climate system is modeled within each SCC-IAM; and
- there are significant observed differences in the global climate responses across SCC-IAMs and the regional temperatures derived by downscaling (i.e., by establishing geographically fine-scale information from changes in aggregate climate conditions).

Chapter 4 explores the relevant aspects of the climate systems of the SCC-IAMs in greater technical detail.

Another aspect in which the SCC-IAMs differ is in the handling of damages. The models differ in the spatial and sectoral resolution of damages, and they differ in which sectors are the most important sources of climate damages. For two of the models (Dynamic Integrated Climate-Economy Model [DICE], and PAGE), damages are functions of only temperature and income, while for the other (FUND) they are also functions of the rate of temperature increase, CO_2 concentrations, per capita income, population, and other drivers.

Overall, each SCC-IAM follows roughly the same causal chain in terms of the sequence of modeling information flow, yet differs in the model translations at each step. The IWG uses the following versions of three IAMs (IWG 2013, 2015):

[10]As designed, each of the three SCC-IAMs derives emissions from socioeconomic projections. However, in the IWG application of those models, socioeconomic and emissions projections were taken from an external source for two of the models, while the third derived its own fossil fuel combustion and industry CO_2 emissions.

- the 2010 version of DICE by William Nordhaus;
- version 3.8 of FUND by Richard Tol and David Anthoff; and
- the 2009 version of PAGE model by Chris Hope.

We note, however, that the IWG model version may be different from the modeler's original or most recent versions.

As mentioned above, the three models differ in the details of their implementation. Table 2-1 provides a broad summary of their dimensions. For a more comprehensive comparison of those differences, see Rose et al. (2014). Specific differences in socioeconomic and emissions modeling are described below, and, in Chapter 4, we discuss climate system modeling.

TABLE 2-1 SCC-IAM Coarse Feature Comparison

	DICE 2010	FUND v3.8	PAGE 09
Regions	1 region	16 regions	8 regions
Damage Sectors	2 sectors	14 sectors	4 sectors
Regional Temperature Downscaling	No	Yes	Yes
Damage Drivers	Temperature (level), income (total)	Temperature (level and growth), CO_2 concentration, income (total and per capita), population size/composition, other[a]	Temperature (level), income (total and per capita)
Sea Level Rise (SLR) Damage Specification	Quadratic function of global sea level rise (i.e., Damage = αSLR^2)	Additive functions for coastal protection costs, dryland loss, and wetland loss, based on an internal cost-benefit rule for optimal adaptation	Power function of global sea level rise (i.e., Damage = $\alpha SLR^{0.7}$)
Damage Specification (Excluding Sea Level Rise)	Quadratic function of global temperature (i.e., Damage = αT^2)	Uniquely formulated by sector	Power function of regional temperature (i.e., Damage = $\alpha T^{1.76}$)
Model-Specific Parametric Uncertainties	None	Yes (in climate and damage modeling)	Yes (in climate and damage modeling)
"Catastrophic" or "Discontinuity" Damages Included	Yes (as expected damages)	No	Yes (as uncertain threshold)

[a]"Other" includes: dryland value, wetland value, topography (elevation, coast length), protection cost, ocean temperature, and technological change.
SOURCE**:** Developed from Rose et al. (2014). Reprinted with permission.

As can be seen in the table above, there are several high-level structural differences among the SCC-IAMs. DICE is global (i.e., has only 1 region), while FUND and PAGE split the world into 16 and 8 regions, respectively. Each SCC-IAM covers multiple damage sectors, but only FUND disaggregates economic sectors in any detail. Since DICE is a global model, only FUND and PAGE downscale regional temperatures (with different methods).

The models also differ in the specific drivers of climate damages and their functional specification. DICE and PAGE use power functions—a quadratic or other polynomial function of temperature or sea level rise—for each of the represented sectors. FUND, on the other hand, disaggregates damage functions into a more detailed set of sectors. In addition, FUND and PAGE both consider model-specific climate and damage parametric uncertainty—each of those models allows for certain parameters to be drawn from probability distributions. Thus, FUND and PAGE reflect some uncertainty in their specifications; however, those characterizations and their implications vary between the two models (see Rose et al., 2014).

METHODOLOGY

The IWG methodology for constructing the official U.S. SCC estimates is discussed in detail in the IWG technical support documents (Interagency Working Group on the Social Cost of Carbon, 2010, 2013, 2015). The methodology results in 150,000 estimates of the SCC for each year and discount rate, yielding a frequency distribution of SCC results; see Figure 2-2. Percentiles and summary statistics of these estimates, also shown in Figure 2-2, are presented in the IWG technical support documents.[11]

In order to arrive at the 150,000 estimates for each discount rate, each of the three models was run 10,000 times with random draws from the equilibrium climate sensitivity (ECS) probability distribution (and other model-specific uncertain parameters), for each of the five socioeconomic scenarios (150,000 estimates = three models × five socioeconomic scenarios × 10,000 runs), for each of three discount rates (2.5 percent, 3 percent, and 5 percent).[12] Frequency distributions of results for 2020 estimates were summarized for each model, socioeconomic scenario, and discount rate.

To facilitate the use of the SCC in regulatory analysis, the values of the SCC are averaged across the three SCC-IAMs and the five emissions scenarios, implicitly defining a frequency distribution of SCC values conditional on each discount rate. In averaging the results across models and emissions scenarios, all models and all emissions scenarios are given equal weight. Figure 2-2 is an example of the resulting frequency distribution for 2020 SCC estimates as reported in the IWG's 2015 technical support documents.[13] The average value of the SCC is shown for each discount rate, using a vertical line, as is the 95th percentile of the frequency distribution of SCC results for the case of a 3 percent discount rate. The larger SCC estimates in Figure 2-2 arise, in part, from realizations in the positively skewed right tail of the ECS distribution used by the IWG.

[11] The full set of estimates is available on request from the IWG.

[12] In terms of standardized uncertainties across all three models, five reference socioeconomic and emissions scenarios projected until 2300 were used, as well as one common probability distribution for the ECS parameter—the equilibrium temperature change that results from a doubling of CO_2 relative to preindustrial levels. For FUND and PAGE, the IWG methodology included model-specific parametric uncertainties for both the climate and damage components.

[13] Summary statistics of the distribution of results for each model, conditional on discount rate and socioeconomic scenario are reported in an appendix of the IWG's technical support document (Interagency Working Group on the Social Cost of Carbon, 2010, Appendix).

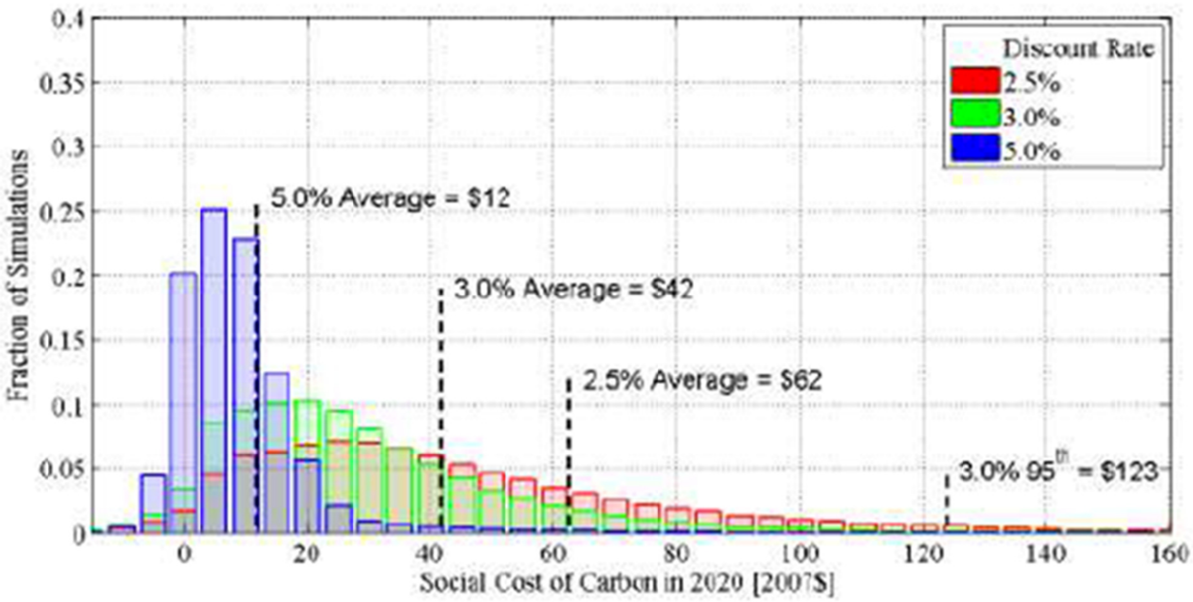

FIGURE 2-2 Frequency distributions of SCC estimates for 2020 (in 2007 dollars per metric ton CO_2).
NOTES: Each histogram (red, green, blue) represents model estimates, conditional on one of three discount rates, over five different socioeconomic-emissions scenarios, 10,000 random parameter draws, and the three SCC-IAMs (see text for discussion). The frequency distributions shown represent most of the 150,000 SCC estimates. However, they do not represent the entire distribution. Some estimates fall outside the range of the horizontal axis shown.
SOURCE: IWG Technical Support Document (Interagency Working Group on the Social Cost of Carbon, 2015, Figure 1).

In the appendix to each technical support document, the frequency distribution of results based on 10,000 runs is summarized for the year 2020 for each SCC-IAM, emissions scenario, and discount rate. Specifically, the average value of the SCC is reported, as well as the 1st, 5th, 10th, 25th, 50th, 75th, 90th, 95th, and 99th percentiles of the frequency distribution of SCC estimates. Table 2-2 illustrates this for a discount rate of 3 percent for each emissions scenario (i.e., 15 sets of results).

TABLE 2-2 2020 Global SCC Estimates at a 3 Percent Discount Rate (2007 dollars/metric ton CO_2).

Percentile	1st	5th	10th	25th	50th	Avg	75th	90th	95th	99th
Scenario					PAGE					
IMAGE	4	7	9	17	36	87	91	228	369	696
MERGE Optimistic	2	4	6	10	22	54	55	136	222	461
MESSAGE	3	5	7	13	28	72	71	188	316	614
MiniCAM Base	3	5	7	13	29	70	72	177	288	597
5th Scenario	1	3	4	7	16	55	46	130	252	632
Scenario					DICE					
IMAGE	16	21	24	32	43	48	60	79	90	102
MERGE Optimistic	10	13	15	19	25	28	35	44	50	58
MESSAGE	14	18	20	26	35	40	49	64	73	83
MiniCAM Base	13	17	20	26	35	39	49	65	73	85
5th Scenario	12	15	17	22	30	34	43	58	67	79
Scenario					FUND					
IMAGE	-13	-4	0	8	18	23	33	51	65	99
MERGE Optimistic	-7	-1	2	8	17	21	29	45	57	95
MESSAGE	-14	-6	-2	5	14	18	26	41	52	82
MiniCAM Base	-7	-1	3	9	19	23	33	50	63	101
5th Scenario	-22	-11	-6	1	8	11	18	31	40	62

SOURCE: IWG Technical Support Document (Interagency Working Group on the Social Cost of Carbon, 2015, Table A.3).

The official SCC estimates are reproduced in Table 2-3 below. For the given years of a CO_2 emission (2010, 2015, 2020, etc.), the four estimates are the average SCC values conditional on the three discount rates, plus the 95th percentile of SCC estimates using a 3 percent discount rate. As noted in the IWG technical support document 2015 update (p. 2):

> Three values are based on the average SCC from three integrated assessment models [SCC-IAMs], at discount rates of 2.5, 3, and 5 percent. The fourth value, which represents the 95th percentile SCC estimate across all three models at a 3 percent discount rate, is included to represent higher-than-expected impacts from temperature change further out in the tails of the SCC distribution.

SCC ESTIMATES

In summary, each single estimate of the 150,000 SCC estimates for each discount rate depends on the SCC-IAM used, the socioeconomic and emissions scenario, a draw from the assumed distribution of the ECS, and, for FUND and PAGE, a draw from the distributions of their particular uncertain parameters. The resulting four official SCC estimates for an emissions year are the mean of the 150,000 results for each discount rate, as well as the 95th percentile for the 3 percent discount rate (see Table 2-3).

TABLE 2-3 Revised Social Cost of CO_2, 2010 - 2050 (in 2007 dollars per metric ton of CO_2).

Discount Rate Year	5.0% Avg	3.0% Avg	2.5% Avg	3.0% 95th
2010	10	31	50	86
2015	11	36	56	105
2020	12	42	62	123
2025	14	46	68	138
2030	16	50	73	152
2035	18	55	78	168
2040	21	60	84	183
2045	23	64	89	197
2050	26	69	95	212

SOURCE: IWG Technical Support Document (Interagency Working Group on the Social Cost of Carbon, 2015, Table 2).

The most recent update of the official SCC estimates is shown in Table 2-3. SCC estimates are provided for different future years on the basis of modeling CO_2 pulses applied in each decade (half decade values are interpolations). The SCC estimates rise over time because, in the models, future emissions produce larger incremental damages as the economy grows and temperature rises.

3
Determining Temperature Changes in Response to CO_2 Emissions

This chapter introduces the technical details that underlie the committee's conclusions and recommendations. The role of the equilibrium climate sensitivity (ECS) in determining temperature changes is described. Several additional relevant climate metrics that reflect the state of the literature are discussed.

The first question in the committee's charge is to consider the merits and challenges associated with a near-term revision of the distribution of the ECS. A broad perspective on the relationship between emissions (a key input to the physical climate/carbon cycle model in the social cost of carbon integrated assessment models [SCC-IAMs]) and global mean temperature (the output) is considered in this chapter. Four metrics are of particular importance to the discussion: ECS, transient climate response (TCR), transient climate response to emissions (TCRE), and the initial pulse-adjustment time (IPT); see Box 3-1. In comparison with other metrics used to summarize the relationship between emissions and temperature change, researchers have noted that the ECS is not necessarily the most relevant physical parameter over the nearer-term timeframes particularly important to determining the SCC (e.g., Otto et al., 2013b).

BOX 3-1
Timescales and Key Metrics for Relating CO_2 Emissions to Temperature Change

The response of global mean temperature to climate forcing can be characterized by a number of different metrics, which represent different timescales.

Equilibrium climate sensitivity (ECS) measures the long-term response of global mean temperature to a fixed forcing, conventionally taken as an instantaneous doubling of CO_2 concentrations from their preindustrial levels. The "long-term" timeframe is set by the time it takes for the ocean as a whole to equilibrate with the change in forcing, typically on the order of many centuries to a couple of millennia. ECS is a measure of long-term planetary response, but it is not comprehensive. It includes the effects of atmospheric and ocean processes involving clouds, water vapor, snow, and sea ice. It does not, however, include other, mostly slower processes, that have not, at least until recently, been represented in coupled global climate models, such as those involving vegetation, land ice, or changes in the carbon cycle; see Figure 3-1.

Transient climate response (TCR) measures the transient response of global mean temperature to a gradually increasing forcing. The timeframe on which TCR is measured allows the shallow "mixed layer" of the ocean to approach equilibrium with the changed forcing, but it does not allow equilibration of the deep ocean. In models, TCR is assessed by increasing CO_2 concentrations at 1 percent per year until CO_2 concentrations double in year 70; TCR is the average temperature over the two decades around the time of doubling (years 61-80).

Transient climate response to emissions (TCRE) measures, on a similar timescale as TCR, the ratio of warming to cumulative CO_2 emissions. While the TCRE has become a widely used metric over the past decade, it has a shorter history in the scholarly literature than ECS or TCR, and thus the methods for assessing it are less established. In models, one way of assessing TCRE is from experiments similar to the 1 percent per year increase used to assess TCR, but using emissions rather than a prescribed change in concentrations to drive the experiment (see, e.g., Gillett et al., 2013). The TCRE is then estimated as the ratio of the TCR to the cumulative CO_2 emissions at the time of CO_2 doubling.

The initial pulse-adjustment timescale (IPT) has only recently been a focus of research and does not have a standard name or definition in the research community, but it may be of considerable importance for estimates of the SCC, which are driven by the injection of a pulse emission of CO_2. The IPT measures the initial adjustment timescale of the temperature response to a pulse emission of CO_2 (see. e.g., Joos et al., 2013; Herrington and Zickfeld, 2014; Ricke and Caldeira, 2014; Zickfeld and Herrington, 2015). For example, Joos et al. (2013) assessed the IPT by adding a 100 gigaton (Gt) carbon pulse to baseline emissions that stabilized CO_2 concentrations at a reference level of 389 ppm; the IPT from such an experiment is the time at which peak warming occurs in response to the pulse.

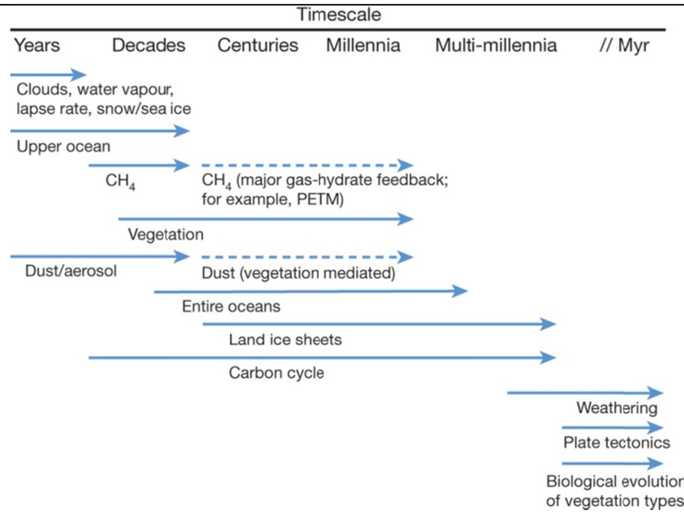

FIGURE 3-1 Different climate processes operate on different timescales.
NOTES: Atmospheric and oceanic processes operating on annual to decadal timescales affect the TCR; these include cloud formation, changes in water vapor, lapse rate, snow and sea ice, as well as heat exchange with the upper ocean. Heat exchange with the deep ocean also affects the ECS. Other processes that can contribute to the global mean surface temperature change caused by a forcing that have not, at least until recently, been included in coupled global climate models are not included in the definition of ECS and TCR. These include changes in vegetation, dust, ice sheets, and the carbon cycle. Some simple climate models do attempt to represent these additional processes.
SOURCE: PALAEOSENS Project (2012, Figure 1).

Modeling the effect of CO_2 emissions on global mean surface temperature entails estimating the effect of emissions on atmospheric CO_2 concentrations, the effect of CO_2 concentrations on radiative forcing, and the effect of forcing on temperature. Although this path is complex, the result appears to be a simpler relationship between temperature and cumulative emissions than between temperature and forcing. As described below ("The Carbon Cycle and TCRE"), the relationship between cumulative CO_2 emissions and global mean temperature change is approximately linear and can be summarized by a single parameter: the transient climate response to cumulative carbon emissions in the industrial era (TCRE). TCRE measures, on a time scale of decades, the ratio between CO_2-induced warming and cumulative emissions, expressed in units of °C/Tt C, where 1 Tt C is 1 trillion tons of fossil carbon or 3.67 trillion tons of CO_2. TCRE is, in turn, determined primarily by TCR (see Matthews et al., 2009; Gillett et al., 2013).

Calculating the SCC entails estimating a baseline temperature trajectory and the temperature response to a pulse of CO_2. The multidecade-to-century warming caused by a pulse of CO_2 can be approximated as the product of the TCRE and the total cumulative amount of carbon injected. The speed of this response, determined by the IPT, is also important for estimating the SCC; see discussion below ("Implications for Estimation of the SCC").

In Chapter 4, the committee details the implications of the discussion in this chapter for calculation of the SCC. The importance of ECS, relative to TCR, depends on the time pattern of damages associated with a time pattern of global temperature change. The higher the fraction of the present discounted value of damages that occur in the first century after emissions, the more important is the TCR relative to the ECS, since the TCR is a much better predictor of climate response on time scales of less than a century. In Chapter 4, the committee outlines tests that could be applied to the simple climate models used to generate the SCC to determine whether the central projections of these models agree with those of the class of Earth system models used by the Intergovernmental Panel on Climate Change (IPCC).[14]

EQUILIBRIUM CLIMATE SENSITIVITY AND TRANSIENT CLIMATE RESPONSE

The concepts of ECS and TCR arise, in their simplest form, from the conservation of energy. In equilibrium, the incoming solar radiation absorbed by Earth balances the outgoing longwave infrared radiation emitted by the planet to space. If either the absorbed solar radiation or the outgoing longwave radiation is perturbed from an equilibrium state, the heat content of the climate system will change at a rate set by the magnitude of the imbalance. The absorbed solar radiation is controlled by the amount of incoming solar radiation and by the Earth's albedo, which is the fraction of the incoming solar radiation reflected away by the atmosphere or the surface. The amount of outgoing longwave radiation is set primarily by the planet's radiative temperature—the temperature of the atmospheric level from which, on average, infrared radiation can be emitted through the "haze" of infrared-absorbing greenhouse gases and clouds to space. Because the radiative temperature increases as the climate system absorbs heat (thereby increasing outgoing longwave radiation) and declines as the climate system loses heat (thereby decreasing outgoing longwave radiation), the imbalance, and thus the rate of temperature change in response to a perturbation, declines over time until a new equilibrium is reached.

A climate forcing (measured in W/m^2 [watts per square meter]) refers to a decrease in net outgoing energy, relative to some initial state in which the planet was in equilibrium, driven by an exogenous factor, such as a change in greenhouse gas or aerosol concentrations. The change in temperature caused by a forcing triggers climate feedbacks: additional changes in the planet's albedo or emissivity that amplify or dampen the energy imbalance and thus cause additional changes in temperatures. Feedbacks involving greenhouse gases and clouds affect emissivity; those involving aerosols, clouds, and land surface characteristics affect albedo. For example, water vapor, which increases in concentration with temperature and thereby decreases emissivity, gives rise to one important amplifying feedback—sea ice—which decreases in surface area with temperature and thereby increases albedo, giving rise to another (amplifying) feedback.

To a good approximation, the equilibrium change in global mean temperature is proportional to the forcing applied. This magnitude is captured by ECS. However, the equilibrium response to a forcing may take centuries to be realized. Within the context of SCC estimates, it is therefore necessary to understand the *transient response* both to the range of human-caused forcings and to a pulse of CO_2, the marginal impact of which the SCC estimates. One common metric of the transient response is the TCR, which is defined as the global mean surface temperature change at the time of CO_2 doubling for a benchmark forcing scenario, specifically, an increase in CO_2 concentrations at a rate of 1 percent per year: see Figure 3-2. Under such a scenario, the time of CO_2 doubling occurs at year 70, and the TCR estimate is generally made by averaging global mean surface temperature over years 61-80. Just as ECS is a general measure of the equilibrium response to any indefinitely sustained radiative forcing, TCR is a general measure of the transient response to a gradually increasing radiative forcing. Because

[14]For formal definitions of IPCC-class Earth system models, see Randall et al. (2007).

the climate system does not instantaneously re-equilibrate in response to a forcing, TCR is always less than ECS.

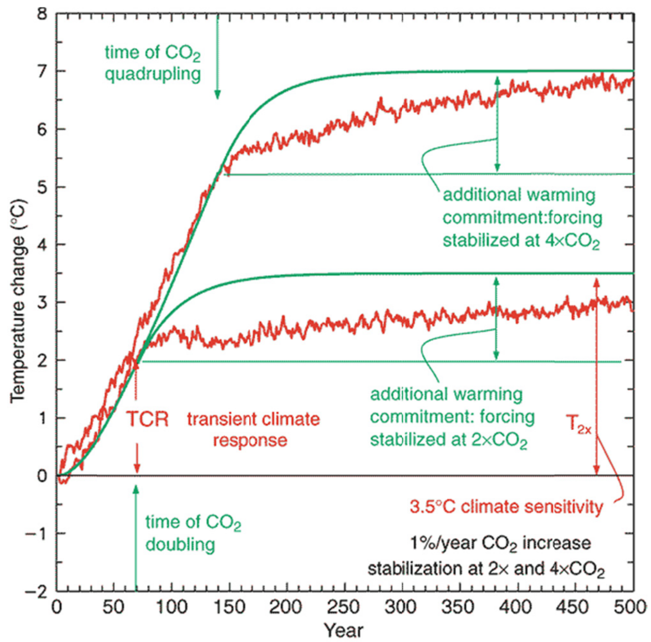

FIGURE 3-2 Global mean temperature response to selected scenarios.
NOTES: CO_2 concentrations increase at 1%/year and stabilize either at two times pre-Industrial CO_2 in year 70 or four times pre-Industrial CO_2 in year 140. Results from a coupled global climate model are shown in red; results from a one-box energy balance model are shown in green. TCR is measured as the average response of the system over years 61-80; ECS is measured after long-term equilibration at two-times CO_2.
SOURCE: Cubasch and Meehl (2001, Figure 9.1).

One source of the difference between ECS and TCR can be observed in a simple "one-box" energy balance model, in which all the heat taken up by the climate system as a result of a forcing is distributed evenly through the climate system as a whole. In such a simple model, the rate of increase in global mean temperature is directly proportional to the rate of heat uptake, with the proportionality set by the heat capacity of the climate system. In response to an instantaneous change in forcing, the temperature of a one-box climate will evolve toward its equilibrium response following an exponential decay with a single timescale. The timescale is directly proportional to both the heat capacity and ECS (see, e.g., Hansen et al., 1985). TCR therefore increases with ECS at a substantially less-than-linear rate: if the TCR is 2°C with an ECS of 3°C, then with the same heat capacity and an ECS of 6°C, TCR will be just 2.8°C.

In contrast to this simple one-box model, full-complexity climate models exhibit two dominant timescales of temperature change in response to a forcing: a fast timescale, associated with the response of the atmosphere and ocean mixed layer (the surface ~100 meters of the ocean), and a slow timescale, associated with the response of the deep ocean. The atmosphere and the mixed layer respond on a timescale of years to a change in forcing, while the deep ocean takes decades to centuries to warm, which slows down the overall response (see, e.g., Hansen et al., 1984; Held et al., 2010). In the scenario used to measure TCR, the mixed layer is nearly fully equilibrated with the applied forcing at the time TCR is assessed, but the deep ocean can be far from equilibrium. These two timescales can be adequately represented in a "two-box" simple climate model that distinguishes between the surface and the deep ocean (see, e.g., Gregory, 2000; Held et al., 2010).

The magnitude of ECS is uncertain due to a number of factors. First, the historical forcing, particularly the historical aerosol forcing, is uncertain (Myhre et al., 2013). Second, as noted, warming lags any radiative forcing, with the strong response implied by a high ECS that takes longer to realize than a weaker response associated with a low ECS. This lag makes it more challenging to distinguish values of ECS observationally. Third, the rate and magnitude of the heat flux from the mixed layer into the deep ocean are uncertain; accordingly, the same transient response can be produced either with a low ECS and faster ocean mixing, or a higher ECS and slower ocean mixing.

A fourth challenge has been identified in recent years: state-dependent feedbacks. Earth's outgoing longwave radiation depends not only on the average radiative temperature, but also on the spatial pattern of temperature, which changes as the planet warms. Accordingly, the rate of energy loss to space also depends on how far the system is from equilibrium (Held et al., 2010). As one example, cloud feedbacks can exhibit state dependence that is represented in atmosphere-ocean global circulation models and Earth system models but not in the simple climate models that specify a fixed ECS value.[15] State-dependent feedbacks can also be related to long-term changes in ocean circulations, land-surface conditions, ocean carbon uptake, and the cryosphere.

This state dependence gives rise to an *effective climate sensitivity*—not ECS, equilibrium climate sensitivity—that is constrained by observations of the recent energy budget constraint. Winton et al. (2010) found that, in 17 of the 22 global climate models participating in the Coupled Model Intercomparison Project Phase 3 (CMIP3),[16] the effective climate sensitivity at the time of CO_2 doubling was less than ECS. Estimates of ECS based on recent climate observations are actually estimates of effective climate sensitivity and may therefore significantly underestimate the true equilibrium response. Unfortunately, there are no clear observational constraints on the relationship between effective and equilibrium climate sensitivity, but this distinction does explain why different approaches to estimating ECS can provide very different ranges (depending on whether or not they assume, implicitly, a specific relationship between the two sensitivity parameters). Although paleoclimatic observations can provide additional constraints on ECS, they are hampered by uncertainties in past forcing and climate data.

Because of these four challenges and the associated uncertainties, the uncertainty in ECS is quite large, with a positively skewed tail of possible high values. A major source of this uncertainty can be seen from the simple treatment of Roe and Baker (2007), whose analysis gave rise to the form of the probability distribution for ECS currently used in the U.S. government's SCC analysis; see Figure 3-3. In the absence of any climate feedbacks other than the "Planck feedback" (by which changes in surface temperature stabilize radiative temperature), ECS would be about 1.2°C (e.g., Hansen et al., 1981). However, other feedbacks come into play. Using f to indicate the total magnitude of these feedbacks on temperature change and ECS_0 the value of ECS including only the Planck feedback gives $ECS = \frac{ECS_0}{1-f}$. The different processes contributing to f add linearly. The positive skewness of the ECS distribution arises from those values of f that approach 1. The Roe and Baker (2007) distributional form for ECS arises simply by assuming

[15]For formal definitions of atmospheric-ocean global circulation models, see Randall et al. (2007).

[16]CMIP provides a standard experimental protocol for IPCC-class global circulation models, and provides community-based support for climate model diagnosis, validation, intercomparison, documentation, and data access.

that *f* has a truncated normal distribution; the associated long right tail would also arise from many other symmetric distributions of *f*.

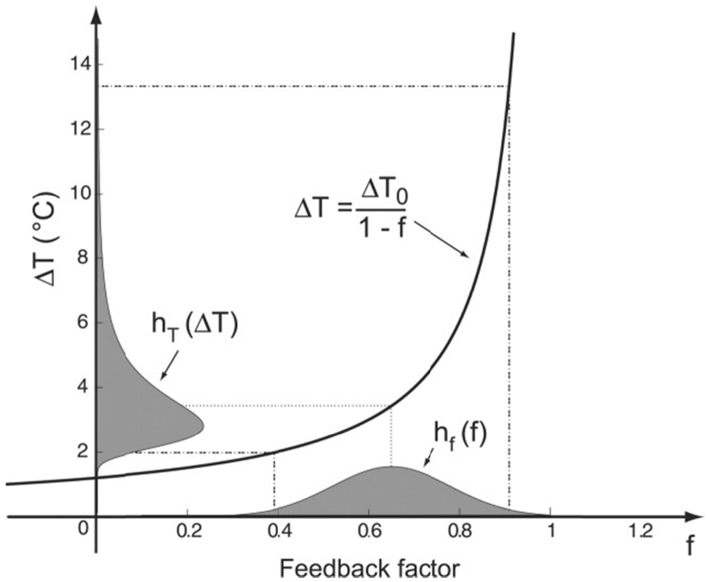

FIGURE 3-3 The relationship between ECS and a feedback factor.
NOTES: The feedback factor is given by $ECS = \frac{ECS_0}{1-f}$ (solid curve). The distributional form for ECS, plotted on the y axis, arises from a truncated normal distribution for the feedback factor, plotted on the x axis.
SOURCE: Roe and Baker (2007, Figure 1). Reprinted with permission from AAAS.

Because larger equilibrium responses caused by higher ECS take longer to realize, TCR is less skewed than ECS (Baker and Roe, 2009). Moreover, whereas ECS may take centuries of data to constrain, the transient response by definition plays out over timescales of less than a century; it can therefore be better constrained by observations (e.g., Gregory and Forster, 2008; Otto et al., 2013a). Box 3-2 describes how IPCC statements regarding the ECS and TCR have evolved from the Fourth to the Fifth Assessment Report (AR4 and AR5), as well as research since the AR5.

ECS and TCR by definition exclude feedbacks—such as those involving dust, vegetation, or land ice—that have not traditionally been represented in coupled climate models. If these other feedbacks are predominantly positive, for the timescales on which they are operative, measures such as ECS and TCR may understate the expected warming. Indeed, geological data suggest that omitted feedbacks may significantly amplify warming relative to that expected based on ECS alone (e.g., PALAEOSENS Project, 2012). Attempts to include relevant processes in Earth system models are a major area of active research. Some simple climate models also attempt to incorporate feedbacks traditionally absent from coupled climate models.

Because the experiments to assess ECS and TCR prescribe only CO_2 concentrations, these metrics also exclude carbon cycle feedbacks. The next section highlights the important role of land and ocean carbon cycle feedbacks in giving rise to CO_2 warming processes operating over millennia.

BOX 3-2
IPCC Estimates of ECS and TCR

The IPCC AR4 concluded

> [on the basis of] observed climate change and the strength of known feedbacks simulated in GCMs [global circulation models] … that the global mean equilibrium warming for doubling CO_2, or "equilibrium climate sensitivity," is likely to lie in the range 2°C to 4.5°C, with a most likely value of about 3°C. Equilibrium climate sensitivity is very likely larger than 1.5°C.

Following the standard interpretation of IPCC likelihood statements (see Table 3-1), the Interagency Working Group on the Social Cost of Carbon (IWG) (Interagency Working Group on the Social Cost of Carbon, 2010) calibrated a Roe and Baker (2007) distribution such that there was a 67 percent probability of a value between 2°C and 4.5°C. Although the IPCC does not detail a specific interpretation for the phrase "most likely," the IWG interpreted it as indicating the median of the calibrated distribution.

The IPCC AR5 revised this assessment of ECS:

> ECS is likely in the range 1.5°C to 4.5°C with high confidence. ECS is positive, extremely unlikely less than 1°C (high confidence), and very unlikely greater than 6°C (medium confidence).

Two changes between AR4 and AR5 are noteworthy. First, AR5 provided no "most likely" value. Second, AR5 reduced the lower bound of the likely range to 1.5 ºC, which was also the value used in the First, Second, and Third Assessment Reports, largely in response to a set of studies based on comparisons of climate observations, extended into the most recent decades, with simple climate models. Subsequent work (Andrews et al., 2012; Gregory et al., 2015; Knutti et al., 2015) has noted that many of these approaches neglected the difference between effective climate sensitivity and ECS, and so these values may underestimate ECS.

Regarding TCR, whereas AR4 concluded that TCR was "very likely above 1°C" and "very likely below 3°C" (i.e., an 80% probability of being between 1°C and 3°C),[a] the AR5 concluded

> with high confidence that the TCR is likely in the range 1°C to 2.5°C, close to the estimated 5 to 95% range of CMIP5 [Coupled Model Intercomparison Project Phase 5] (1.2°C to 2.4°C), is positive and extremely unlikely greater than 3°C.

The AR5 thus reduced the probability of TCR values greater than 3°C from 10 percent to 5 percent. The estimate was based on the good agreement between the range of estimates from observationally constrained simple climate models and the CMIP5 range. One major driver of this change in observational estimates was the downward revision of the negative aerosol forcing. This revision reduced the probability that the historically observed warming was a response to a very low total forcing, which thereby reduced the probability of a correspondingly high TCR.

The consensus on TCR appears to have been maintained since the publication of the AR5: for example, despite being critical of the IPCC's estimates of ECS, Lewis and

Curry (2014) arrive at a 5 to 95 percent confidence interval for TCR of 0.9°C-2.5°C, almost identical to the IPCC AR5 "likely" range. (IPCC statements on indirectly observable quantities are typically given at one level lower confidence than the formal evidence suggests, to account for unknown structural uncertainties). The only dissent is from Shindell (2014), who argues that TCR estimates based on recent observations may have been biased low by the assumption that spatially homogenous and inhomogenous forcings have identical efficacy. The attribution approach of Gillett et al. (2013), however, does not make this assumption of equal efficacies, and it arrives at a 5 to 95 percent range for TCR of 0.9°C-2.3°C. In contrast to TCR, ECS remains much more contested.

In summary, the change in the ECS distribution between AR4 and AR5 is small relative to the remaining uncertainties in this and other parameters that determine the SCC. This change arose primarily from assumptions about the multicentury adjustment of the climate system to a constant forcing that remain contested in the literature since the AR5. Neglected processes primarily affect the upper bound on ECS, continuing to support a positively skewed distributional form for this parameter such as that used by Roe and Baker (2007). The AR4 did not give a likely range for TCR that is directly comparable to that in the AR5, but the AR5 did reduce the probability of TCR values greater than 3°C from 10 to 5 percent, reflecting greater confidence and consensus on the upper bound for this parameter.

TABLE 3-1 AR5: Likelihood Scale

Term*	**Likelihood of the Outcome**
Virtually certain	99-100% probability
Very likely	90-100% probability
Likely	66-100% probability
About as likely as not	33-66% probability
Unlikely	0-33% probability
Very unlikely	0-10% probability
Exceptionally unlikely	0-1% probability

*Additional terms that were used in limited circumstances in the AR4 (*extremely likely,* 95-100% probability; *more likely that not*, >50-100% probability; and *extremely unlikely,* 0-5% probability) may also be used in the AR5 when appropriate.
SOURCE**:** Mastrandrea et al. (2010, Table 1). Reprinted with permission from Macmillan Publishers Ltd.

[a]The terms "most likely value," "likely," "very likely," and "zero probability" are the keys to translating the uncertainty information into probability distributions representing the IPCC assessments; see Table 3-1 for more details.

THE CARBON CYCLE AND TCRE

The discussion so far has focused on the response of global mean surface temperature to a particular level or time path of greenhouse gas concentrations in the atmosphere. To fully understand the response of temperature to CO_2 emissions, one must also understand how CO_2 emissions translate into atmospheric concentrations, how atmospheric CO_2 concentrations translate into forcing, and how forcing translates into temperature change.

For CO_2, the relationship between concentrations and forcing is fairly straightforward. To a good approximation, the radiative forcing of CO_2 is logarithmic in concentration (Arrhenius, 1896). This logarithmic relationship means that, for higher CO_2 concentrations, further incremental increases in the CO_2 concentration yields a diminishing increase in the CO_2 forcing.

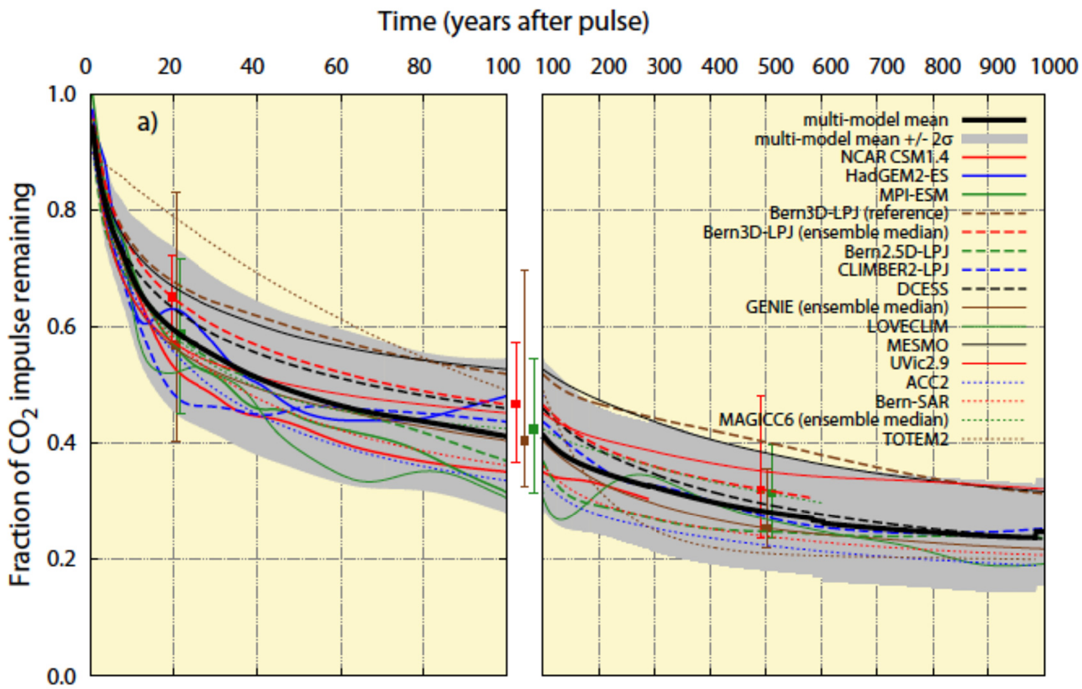

FIGURE 3-4 The perturbation to atmospheric CO_2 concentrations in response to an emission pulse.

NOTES: The figure uses an emission pulse of 100 billion tons of carbon (367 Gt CO_2) added to an atmospheric background concentration of 389 ppm, expressed as the fraction of the initial pulse remaining in the atmosphere for a range of Earth system models (thick solid lines), intermediate complexity (dashed and thin solid lines), and simple climate models (dotted lines). A value of 1.0 corresponds to an increase in CO_2 concentrations of 47.2 ppm. The multimodel mean, computed by giving each available model equal weight, and the corresponding ± two standard deviation range is shown by the black solid line and the grey shading.

SOURCE: Joos et al. (2013, Figure 1a). with caption reproduced, slightly edited for clarity.

The relationship between emissions and concentrations is more complicated, as it involves the full carbon cycle, including some crucial feedbacks between concentrations, temperatures, and fluxes. When a ton of CO_2 is emitted into the atmosphere, a small fraction, about 20 percent, is removed within the first 5 years by the land biosphere and by the ocean, so that about 80 percent is still airborne; see Figure 3-4. After 20 years, about 40 percent of the emitted ton has been thus taken up, and about 60 percent is still airborne; after 100 years, about 60 percent has been removed from the atmosphere and about 40 percent is still airborne. Over the course of the following centuries, the oceans become the major repository of the added carbon.

There are two major bottlenecks in the ocean uptake of CO_2. The first is across the air-sea interface: the CO_2 partial pressure in the surface oceans, i.e., the pressure pushing CO_2 back into the atmosphere, increases with carbon uptake and the accompanying decrease in pH. The second is below the mixed layer, where carbon is mixed into the deeper ocean on multicentennial timescales. Yet even on multicentennial timescales, the carbonate chemistry and the ocean volume dictate that oceans cannot absorb 100 percent of the added carbon, and about 20 percent will remain in the atmosphere after a millennium (Broecker et al., 1979). The ultimate carbon sink occurs through weathering reactions and sedimentation on the ocean floor, which takes place on time scales of hundreds of thousands of years (Archer et al., 2009; Ciais et al., 2013).

The effect of climate change on the carbon cycle gives rise to an amplifying feedback between atmospheric CO_2 and temperature. Warming accelerates decomposition on land faster than CO_2 fertilization increases the rate of photosynthesis, weakening the land-carbon sink (Friedlingstein et al., 2006). Warming also further stratifies the oceans, slowing the penetration of heat and carbon to the deep ocean. The decreasing pH and the warmer temperatures (decreasing solubility) also shift the equilibrium of the carbonic acid/bicarbonate buffer and reduce the ocean absorption of CO_2 from the atmosphere (Archer and Brokin, 2008).

The weakening of the land and ocean carbon sinks as a result of warming increases the atmospheric residence time of CO_2 (Jones et al., 2013), giving rise to a convex relationship between cumulative carbon emissions and atmospheric CO_2 concentrations. When the convex relationship between emissions and concentrations is combined with the concave relationship between concentrations and forcing, the result is a coincidental cancellation that results in a nearly linear relationship between cumulative CO_2 emissions and radiative forcing.

The global mean surface temperature also responds approximately linearly to a continually increasing effective radiative forcing (Flato et al., 2013). Hence, provided the forcing is increasing slowly relative to the response time of the ocean mixed layer (Held et al., 2010), there is a linear relationship between the forcing at any given time and the resulting warming at that time. (Note that this warming is generally not in equilibrium with the forcing.) When the nearly linear relationship between cumulative CO_2 emissions and forcing is combined with the linear relationship between forcing and temperature, the result is a simple, nearly linear relationship between cumulative carbon emissions and the resulting warming (Goodwin et al., 2015).

Another cancellation, between the gradual decline of atmospheric CO_2 and the slow approach of the ocean to thermal equilibrium, causes temperatures to remain nearly constant for centuries following a complete cessation of CO_2 emissions (Matthews and Caldeira, 2008; Solomon et al., 2009). This cancellation arises because both of these processes operate on similar timescales set by the mixing of carbon and heat into the deep ocean; see Figure 3-5.

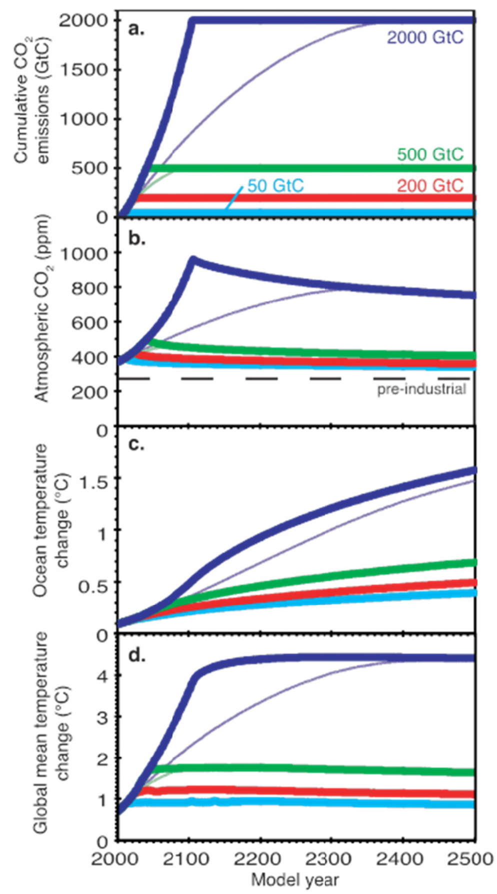

FIGURE 3-5 The response of an Earth system model of intermediate complexity to different levels of cumulative emissions
NOTES: The four responses reveal the long-lived nature of the CO_2-forced warming: (a) scenarios of cumulative CO_2 emissions, (b) resulting atmospheric CO_2 concentrations, (c) associated change in mean ocean temperature, and (d) associated change in global mean surface temperature. The combination of declining atmospheric CO_2 and increasing mean ocean temperature give rise to a nearly stable global mean surface temperature after the cessation of emissions.
SOURCE: Matthews and Caldeira (2008, Figure 2). Reprinted with permission.

A series of papers published in the late 2000s (e.g., Allen et al., 2009; Matthews et al., 2009; Meinshausen et al., 2009; Zickfeld et al., 2009) pointed out that, as a consequence of the longevity of the warming associated with CO_2 emissions, temperatures in any given year were largely determined by cumulative CO_2 emissions up to that time. Gillett et al. (2013) updated the carbon budget estimates in these early papers to take into account updated estimates of the strength of anthropogenic forcing and the evolution of global temperatures since 2000; see Figure 3-6. In the AR5, Collins et al. (2013, p. 1033) concluded that “the principal driver of long-term warming is total emissions of CO_2 and the two quantities are approximately linearly related.”

The approximately linear relationship between cumulative CO_2 emissions and the warming it causes simplifies the estimation of the climate response to CO_2 emissions. It means that the global mean temperature change induced by CO_2 can be largely summarized by a single parameter, the TCRE.

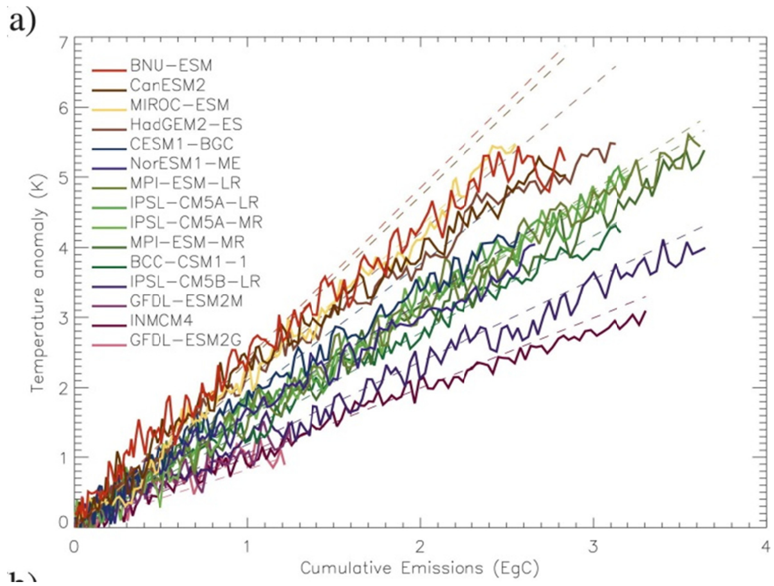

FIGURE 3-6 Temperature anomaly plotted against cumulative CO_2 emissions.
NOTES: The data are from the 1 percent/year CO_2 increase experiment for Earth system models participating in CMIP5. Dashed curves are lines with constant slope. The data show approximate linearity of warming in cumulative CO_2 emissions up to 1.5-2.0 exagrams of carbon (EgC) cumulative carbon emissions.
SOURCE: Gillett et al. (2013, Figure 1a). ©American Meteorological Society. Used with permission.

Herrington and Zickfeld (2014) show that the TCRE is a robust measure of the climate response, regardless of the timescale of injection for realistic emission scenarios, although the response takes up to a century to stabilize for very large instantaneous CO_2 pulses. The AR5 (Collins et al., 2013) suggested the TCRE was approximately constant for cumulative injections up to 2 teratons of carbon (Tt C), although Herrington and Zickfeld (2014), consistent with Allen et al. (2009), suggest it declines slightly for cumulative emissions in excess of 1.5 Tt C. Gillett et al. (2013), with a broader range of models, find evidence for a smaller decline, with any departure from linearity being small relative to uncertainty in the response (Figure 3-6).

TCRE is determined by two quantities. First, TCRE depends on the cumulative airborne fraction at the time of CO_2 doubling (or, approximately equivalently, after a cumulative release of 1 Tt C in the form of CO_2) following a gradual increase in concentrations over a multidecade period. This fraction is between 0.47 and 0.67 in current climate models (Gillett et al., 2013). Second, TCRE depends on the warming at the time of CO_2 doubling following a gradual increase in concentrations, or the TCR. Most of the uncertainty in TCRE arises from the uncertainty in TCR, leading to an AR5 consensus "likely" range, accounting for both model and observational lines of evidence, of 0.8°C-2.5°C/Tt C, which is equivalent to 0.2°C-0.7°C/1000 Gt CO_2 (Collins et al., 2013).

While uncertainty in ECS gives rise to uncertainty in the additional warming that would occur over centuries if atmospheric CO_2 concentrations were stabilized, current comprehensive Earth system models indicate that uncertainty in ECS is largely irrelevant to TCRE and hence to the temperature response to a pulse injection of CO_2. This irrelevancy occurs because, after a cessation of emissions, atmospheric CO_2 concentrations do not stabilize, but rather fall just fast enough that the "recalcitrant" warming reflected by ECS (Held et al., 2010) never materializes (Matthews and Caldeira, 2008; Solomon et al., 2009).

TEMPERATURE EFFECT OF A CO_2 PULSE AND THE INITIAL PULSE-ADJUSTMENT TIME

The constancy of the TCRE indicates that the multidecade-to-century-timescale climate response to any CO_2 injection can be accurately approximated by a constant temperature increase set by the total cumulative amount of carbon injected and the TCRE. A key remaining aspect of the response that is relevant to the SCC is the form and speed of the adjustment immediately following a pulse injection of carbon. The most comprehensive study to date to address this question was the multimodel comparison of Joos et al. (2013). They examined the impact of a 100 Gt C pulse injection of CO_2, relative to a baseline scenario in which CO_2 concentrations were held constant at 389 ppm following a historical transition to that point in a range of simple climate models and Earth system models of both intermediate and full complexity.

Results are shown in Figure 3-7, with solid lines corresponding to full-complexity models, dashed lines to intermediate-complexity models, and dotted lines to simple models. The full-complexity models display large fluctuations that can be understood entirely as random internal variability, given the small size of the temperature response even to a pulse of this magnitude (comparable to about a decade of CO_2 emissions at 2015 levels). Strikingly, all models, including the most complex, adjust relatively rapidly, with temperatures rising to about 0.2°C within 10 to 20 years of the pulse and then remaining constant for the remainder of a century. A slight decline is observed over the millennium (right panel).

In modeling the carbon cycle response to this pulse injection, Joos et al. (2013) find a very rapid IPT of only a few years and very slow subsequent adjustments on multidecade and multicentury timescales. The short IPT in Figure 3-7 is primarily set by the ocean mixed-layer thermal response time, which is known, on physical grounds, to be of the order of a decade or less (Held et al., 2010). The adjustment to a pulse injection of CO_2 can thus be adequately characterized by an initial adjustment within a timeframe of 4 years to a decade, followed by stable temperatures for a century and slow decline thereafter.

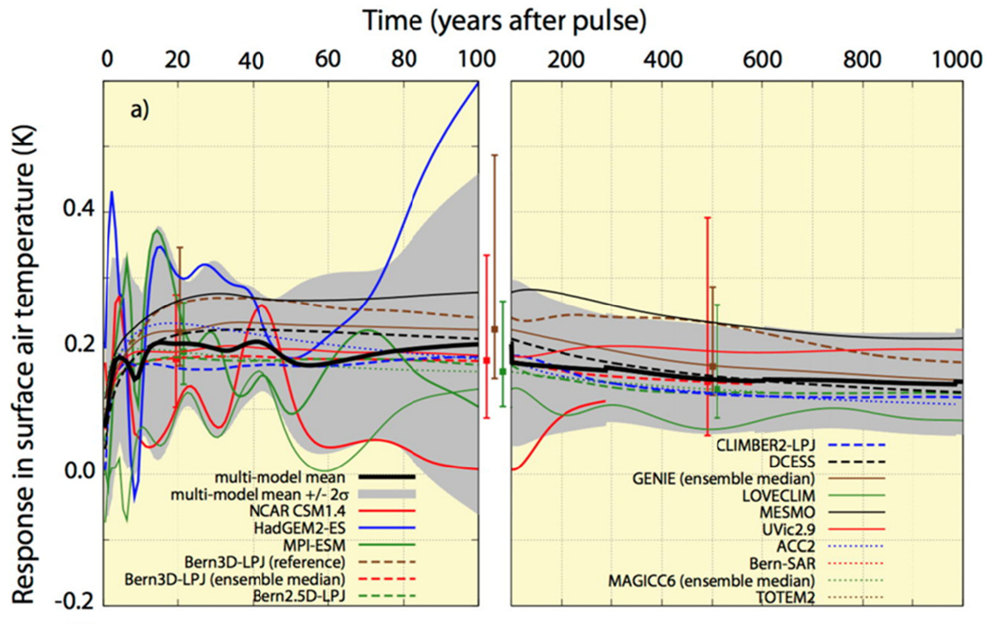

FIGURE 3-7 Response of global mean temperature to a 100 GtC pulse emission of CO_2.
NOTES: The data are from the same experiments shown in Figure 3-4 (above), with temperature change expressed relative to a stable baseline CO_2 concentration of 389 ppm. Participating full-complexity Earth system models (solid curves) have a high degree of variability. The Earth system models of intermediate complexity and simple climate models are shown with dashed and dotted lines, respectively.
SOURCE: Joos et al. (2013, Figure 2a).

Ricke and Caldeira (2014) use a simple climate model that combines a carbon cycle model fit to the results of Joos et al. (2013) with a simple model of the thermal response (similar to that of Held et al. [2010]) to obtain the temperature response to a pulse CO_2 emission. They find that temperature peaks between 7 and 31 years after the emissions (90% probability range, median of 10 years). While their simple climate model suggests a modest decline in temperatures after the peak, this finding arises from the lack of explicit climate carbon cycle feedback in their composite model, and it is not evident in the more complex models on which their composite model is based (Joos et al., 2013). In order for a simple climate model to generate the near linearity of warming in cumulative carbon emissions, as well as the longevity of the associated warming, it is necessary to use either a carbon cycle model that includes the effects of pH and warming on CO_2 solubility (e.g., Glotter et al., 2014), the impact of warming on land carbon sinks (e.g., Friedlingstein et al., 2006; Allen et al., 2009), or a direct approximation of the linearity in cumulative carbon emissions (e.g., Kopp and Mignone, 2013).

On the basis of the current evidence, the committee concludes that the likely approximation for characterizing the response over annual-to-centennial timescales of the climate system to a pulse of emissions of CO_2 is a simple rapid adjustment (4 years to one decade) to the level of warming indicated by the TCRE, with modest decline for at least a century thereafter.[17] As noted in Chapter 4, experiments like those of Joos et al. (2013) can be used to evaluate the SCC-IAM climate modeling.

IMPLICATIONS FOR ESTIMATION OF THE SCC

To estimate the SCC, it is necessary to project both the physical climate changes associated with a baseline emissions trajectory and the effect of a small, additional pulse of CO_2 emitted on top of that baseline trajectory.[18]

While the TCRE and IPT are relevant for capturing the response to cumulative or pulse emissions of CO_2, other measures are relevant for computing a baseline climate, which may be influenced by CO_2 emissions high enough (greater than approximately 1.5 Tt C) that the TCRE is not constant and is also affected by non-CO_2 forcers. The relative importance of TCR and ECS in characterizing the SCC depends on the relative proportion of net present value damages that occur in roughly the first century of emissions. By construction, TCR is a much better predictor than ECS of the climate response on timescales of less than a century.[19] As a result, Otto et al. (2013b) found that in their simple model for estimating the SCC, for a moderate emissions trajectory[20] and a quadratic damage function, reducing uncertainty in TCR leads to a greater reduction in SCC uncertainty than reducing uncertainty in ECS, provided that the discount rate is at least about 1 percent higher than the growth rate of consumption; see Figure 3-8. For highly convex damage functions and discount rates sufficiently close to the consumption growth rate, Otto et al. (2013b) found that learning about ECS leads to a greater reduction in SCC uncertainty than learning about TCR.

Factors that increase the fraction of the SCC due to damages after the first century, and thus increase the importance of ECS in comparison with TCR, include an increase in baseline temperatures as well as economic factors. In climate damage functions, such as those used in the SCC-IAMs, faster economic growth for a given discount rate or a lower discount rate for given economic growth will both tend to increase the importance of the more distant future and thus the ECS. In this context, it is worth noting that the IWG analysis holds the discount rate constant but assumes a decrease in growth rates after 2100, thereby increasing the importance of TCR over ECS relative to a constant growth-rate scenario or one in which the discount rate declines when the growth rate declines. In the 21st century, the average economic growth rate in the IWG scenarios ranges between 2.0 and 2.4 percent per year, while over 2100-2300 it ranges between

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[17]Joos et al. (2013) found that the magnitude of the temperature response to a pulse injection (0.20 ± 0.12°C/100 Gt C) is comparable to—though slightly higher than—the AR5 range for TCRE, although their analysis was based on a subset of the models used by the AR5 for its statement on TCRE. In single-model studies, Herrington and Zickfeld (2014) and Zickfeld and Herrington (2015) found that TCRE falls with both the speed and magnitude of a pulse injection, while Krasting et al. (2014) found that TCRE is larger for both small (~2 Gt C/yr) and large (~20 Gt C/yr) rates of emissions than for current rates of emission (~10 Gt C/yr).

[18]This requirement can be seen in a simple, typical model: If damages are equal to economic output times a power function of temperature, $D(T) = aT^b$, then the change in damages associated with an emission pulse that shifts temperature from T to $T + \Delta T$ at time t is proportional to $T(t)^{b-1}\,\Delta T(t)$. Thus, the physical climate model underlying the SCC calculation must provide reasonable projections for both $T(t)$ and $\Delta T(t)$; that is, both the baseline temperature response and the long-term temperature changes due to an emissions pulse. The economic valuation also depends on the relative sizes of the growth rate of consumption and the rate at which damages are discounted.

[19]This finding can be seen from the 1 percent/year CO_2 concentration growth scenario used to define TCR, in which ECS provides no additional information about the temperature response until after year 70.

[20]Otto et al. used representative concentration pathway (RCP) 4.5. RCPs are greenhouse gas concentration trajectories used by the IPCC in AR5 (van Vuuren et al., 2011).

0.5 and 0.9 percent per year.[21] In the context of the Otto et al. (2013b) results, the low growth rates after 2100 suggest that TCR will be a more important determinant than ECS of the SCC calculated using the IWG methodology, even at the lowest discount rate used (2.5% per year).

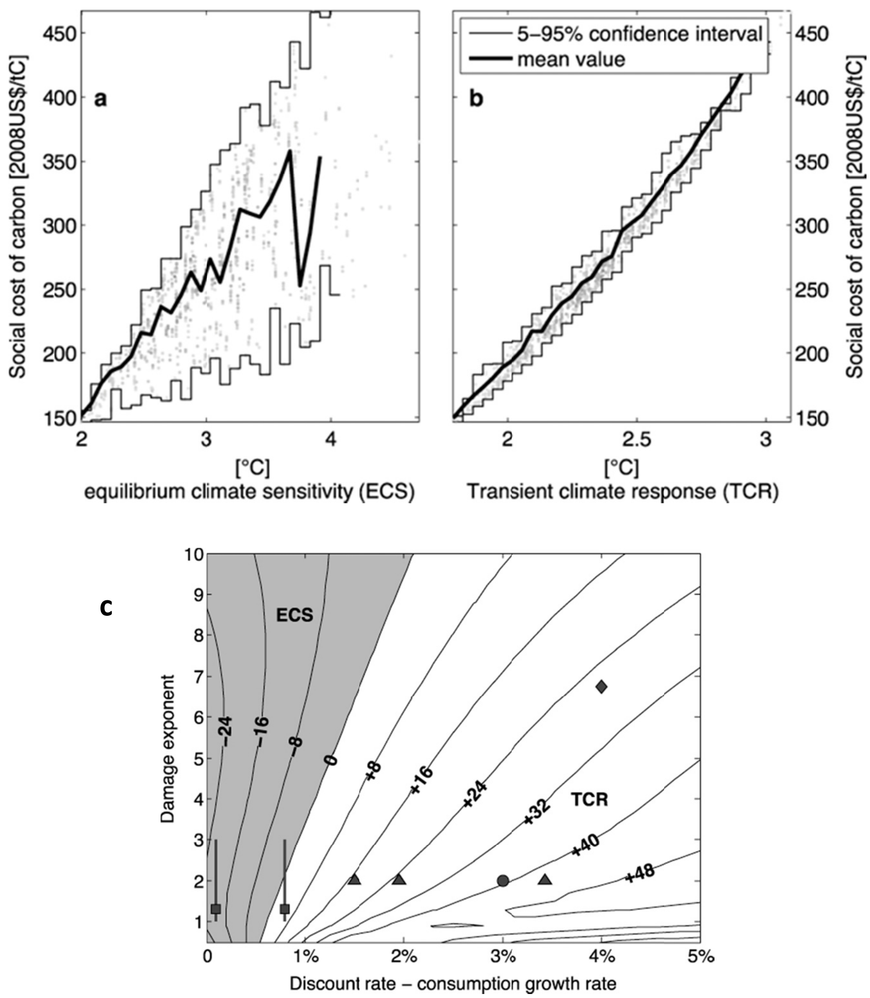

FIGURE 3-8 Impact of information on climate system properties for the SCC.
NOTES: Panel (a) shows the Otto et al. estimates of the SCC allowing for uncertainty in climate and carbon cycle properties plotted as a function of ECS, with the black line showing mean estimate and the shaded region showing 5 to 95 percent range and dots showing individual estimates, all assuming a discount rate minus consumption growth rate of 3 percent and a quadratic damage function [the round dot in panel (c)]. The broad vertical range indicates that learning the value of the ECS does not substantially reduce uncertainty in SCC except at very low values of ECS. Panel (b) shows the Otto et al. estimates of the SCC similarly plotted as a function of TCR. The narrow vertical range indicates that learning the value of TCR substantially reduces uncertainty in SCC. Panel (c) shows the relative benefits of learning the value of ECS or TCR as a function of the discount rate and curvature of the damage function, with high values of the damage exponent corresponding to strongly convex damage functions.

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[21]The IWG used aggregate output (GDP) as a socioeconomic input, not macroeconomic aggregate consumption, which is a component of aggregate output. For this purpose, it is reasonable to think of consumption growth as proportional to output growth.

White/grey regions indicate parameter combinations for which learning TCR is more or less informative than learning ECS.
SOURCE: Adapted from Otto et al. (2013b, Figures 2 and 3). Reprinted with permission.

TCRE is the crucial parameter determining the contribution of the physical climate system response to the SCC, since it determines the magnitude of multidecade-to-century timescale warming resulting from a pulse injection of CO_2. TCRE is primarily determined by TCR, not ECS. Revisions to ECS are therefore relevant to SCC estimation, principally through their possible implications for baseline warming after a century or more. TCR and IPT determine temperature changes over shorter time periods, including the response to a small pulse emission of CO_2. Hence, the revision of the “likely” range of ECS from 2.0°C to 4.5°C in the AR4 to 1.5°C to 4.5°C in the AR5 should have a minimal impact on estimates of the SCC.

4
Climate System Modeling in the SCC-IAMs and the Role of ECS

This chapter provides information on how the social cost of carbon integrated assessment models (SCC-IAMs) currently model the climate system and how equilibrium climate sensitivity (ECS) is incorporated into each SCC-IAM. In addition, the committee outlines tests that could be applied to the simple climate models used to generate the SCC, to determine whether the central projections of these models agree with those of more comprehensive Earth system models.

REPRESENTATION OF THE CLIMATE SYSTEM IN THE SCC-IAMS

The three SCC-IAMs used by the Interagency Working Group on the Social Cost of Carbon (IWG) are the Dynamic Integrated Climate-Economy Model (DICE), the Policy Analysis of the Greenhouse Effect (PAGE) model, and the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model. The climate system in each of them consists of three major elements: calculation of the path of atmospheric concentrations of CO_2 from greenhouse gas emissions, translation of concentrations to radiative forcing, and the response of global mean surface temperature to changes in radiative forcing. However, the specification (structural and parametric) of each element varies across the models; see Table 4-1.[22] Significant differences exist in the structure of the carbon cycle, radiative forcing per doubling of CO_2 concentrations, the derivation of global mean temperature from forcing, the coverage of and interactions with non-CO_2 concentrations and forcing, and climate feedback representation. Differences in model time steps are also meaningful, as they have an impact on the climate system dynamics in the models.

[22]For additional discussion and details, see Rose et al. (2014). This is one of the few systematic reviews and comparisons of the SCC-IAMs; it is used in this chapter to introduce the differences between the three IAMs.

TABLE 4-1 Climate Modeling Structural Characteristics for the SCC-IAMs.

Characteristic	DICE	FUND	PAGE
Atmospheric Concentrations			
CO_2	3-box carbon cycle	5-box carbon cycle	1-box carbon cycle
Non-CO_2 Kyoto	Not modeled	CH_4, N_2O, SF_6	Not modeled
Non-CO_2 non-Kyoto	Not modeled	SO_2	SO_2
Radiative forcing			
CO_2 (per doubling)	3.80 W/m^2	3.71 W/m^2	3.81 W/m^2
Non-CO_2 Kyoto	Exogenous	CH_4, N_2O, SF_6	Exogenous
Non-CO_2 non-Kyoto	Exogenous	SO_2	SO_2, non-SO_2 exogenous
Global Mean Surface Temperature	Rate temperature moves toward equilibrium is a function of climate sensitivity & surface temperature modulated by ocean heat uptake	Rate temperature moves towards equilibrium is a function of climate sensitivity	Function of global mean land and ocean temperatures
Ocean Temperatures	2-box (upper and deep ocean)	1-box	1-box
Regional Temperatures	n/a	Implicit with regional damage parameters calibrated to regional temperatures downscaled based on a linear pattern-scale average of 14 global circulation models	Explicit with regional temperatures downscaled according to latitude and landmass adjustment
Global Mean Sea Level Rise	Components (thermal expansion, glacier and small ice cap melt, GIS melt, WAIS melt) computed as functions of temperature and lagged temperature	Computed as a function of temperature and lagged temperature	Computed as a function of temperature and lagged temperature
Time Steps	10-year	1-year	Variable (10-year 2000-2060, 20-year 2060-2100, 100-year 2100-2300)
Implementation of CO_2 Pulse in Year t	Pulse spread equally over the decade straddling year t	Pulse spread equally over the decade from year t forward	Pulse distributed evenly over the two decades preceding and subsequent to year t
Model-Specific Uncertainties Other than ECS (number of parameters; distribution types)	None	11 – normal, truncated normal, triangular, and gamma distributions	10 – triangular distributions

NOTE: See text for discussion.
SOURCE: Modified from Rose et al. (2014, Table 5-1).

We note that the IWG has modified the SCC climate modeling components of each model. In DICE, the IWG changed the time steps and averaged CO_2 concentrations across time periods. In PAGE, the IWG modified the time-step scheme, the modeling of non-CO_2 emissions and forcing, and the ECD modeling approach.[23] The IWG also standardized the distribution of the ECS used in each model.

[23]Non-CO_2 forcing is also captured in the models in significantly different ways, with FUND deriving non-CO_2 concentrations and forcing, and DICE and PAGE using forcing assumptions developed from sources outside the models. Also, the models vary in their coverage of non-CO_2 forcing, with all three different in total forcing coverage: FUND covers the fewest of the broad set of non-CO_2 forcing constituents, including long-lived and short-lived gases and aerosols.

Differences in the derivation of temperature from forcing are also noteworthy with regard to the IWG's standardization of the ECS distribution. In DICE and FUND, the rate at which temperature moves toward equilibrium is affected by ECS. In these two models, a higher ECS corresponds to a slower convergence toward the equilibrium temperature (i.e., a longer period of time, or lag, before reaching the equilibrium temperature). Varying the adjustment speed (or lag) with the climate sensitivity parameter ensures some consistency with historical observations. Importantly, it also moderates the effect of changing the ECS parameter, in particular on transient climate response (TCR). The temperature response in PAGE, which does not include this temperature lag adjustment, is more sensitive to alternative ECS values. DICE, which uses a two-box ocean model, also includes a moderating feedback from the ocean, with deep ocean temperatures moderating the rate at which surface temperature increases. Finally, FUND and PAGE include an explicit climate carbon cycle feedback that accelerates global warming at higher temperatures. The feedback represents global physical mechanisms (e.g., terrestrial drying and vegetation dieback) that release additional emissions into the atmosphere as the planet warms and in so doing increase the rate of global warming.

Global mean surface temperature is the primary climate variable driving the climate damage estimates in all three of the models. In addition, the rate of temperature change and CO_2 concentrations are also used in some FUND damage categories. Other climate variables such as precipitation, weather variability, and extreme weather events are not modeled explicitly, although these effects may be captured implicitly in the calibration of damage response to global mean temperature change.

Global mean surface temperature drives projected global average mean sea level rise in all three models and projected regional average temperatures in FUND and PAGE, which in turn drive damages. However, differences in the downscaling approach lead to differences in projected regional temperatures across FUND and PAGE for the same global mean surface temperature, with PAGE projecting greater warming for many regions. The sea level rise calculations also vary across models, with projected sea level rise in 2100 varying by a factor of two across models for the same projected levels of warming (Rose et al., 2014).

It is worth noting that in the IWG's SCC methodology, climate system parametric uncertainty is accounted for in all three models, but to different degrees. All models consider ECS parameter uncertainty through a probability distribution for ECS calibrated to the likelihoods of the Intergovernmental Panel on Climate Change (IPCC, 2007), with a distributional form adopted from Roe and Baker (2007). In addition, FUND and PAGE incorporate additional climate-model-specific parametric uncertainties.

In the DICE model, the climate model component is represented using a two-layer ocean (see Chapter 3, "Determining Temperature Changes in Response to CO_2 Emissions"). In FUND and PAGE, the temperature response is characterized by a single exponential decay. In DICE and FUND, the timescale of the temperature response varies with the ECS.[24]

Figure 4-1 shows that the models used in the IWG analysis vary by decades in the time taken to reach peak warming associated with a pulse emission. This contrasts with the time of about one decade indicated by the models participating in the Joos et al. (2013) intercomparison (see Figure 3-7 in Chapter 3). However, direct comparison between the two sets of results is complicated by differences in their experimental design and baselines.

[24]In the standard version of the 2009 PAGE model, the timescale and TCR are parameters, and ECS is a function of them. In the IWG version of PAGE, timescale is invariant to the ECS parameter, and TCR is not an explicit parameter.

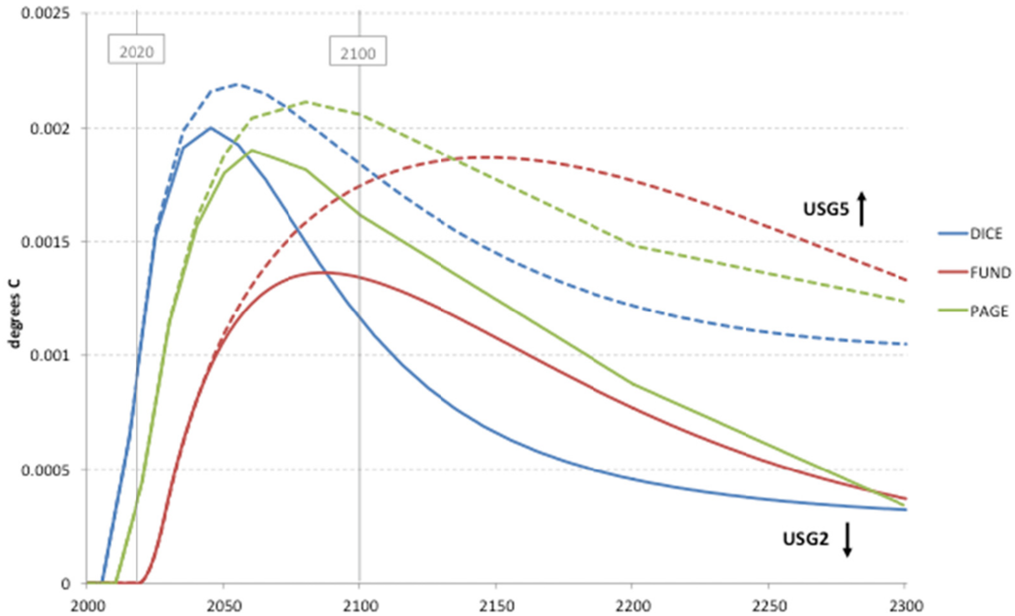


FIGURE 4-1 Incremental annual global mean temperature responses to 2300 from the climate components of the SCC-IAMs.
NOTES: The responses are for a 1 GtC emissions pulse in 2020 with higher (USG2, solid) and lower (USG5, dashed) reference emissions. USG2 and USG5 are the socioeconomic scenarios that produce the highest and lowest fossil fuel and industrial CO_2 emission projections respectively in the IWG methodology. The lower baseline USG5 results (dashed) are more comparable to those from the Joos et al. (2013) experiment shown in Figure 3-7 (in Chapter 3), which performed a pulse experiment on top of a 389 ppm CO_2 baseline. Note that the Joos et al. (2013) experiment is not fully comparable.
SOURCE: Developed from Rose et al. (2014). Reprinted with permission.

Harmonization of Emissions Inputs and the ECS by the IWG

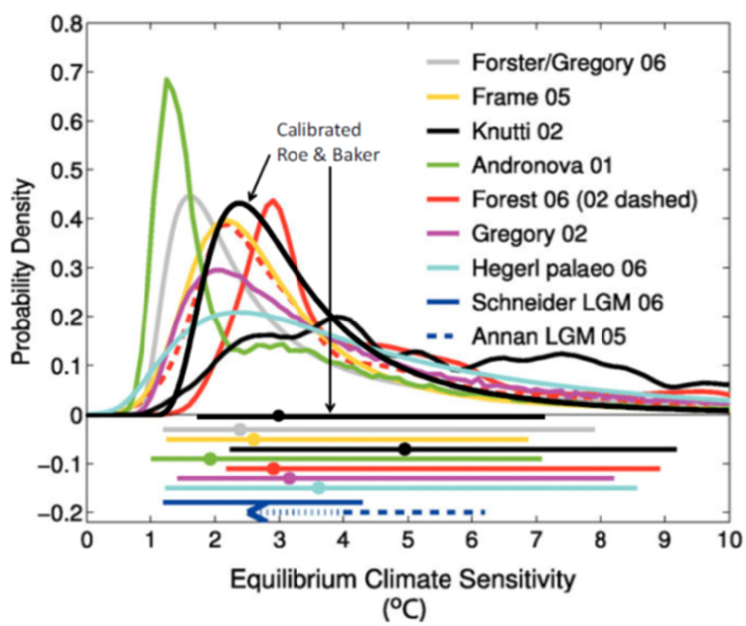
The IWG methodology harmonizes assumptions across the three models along three dimensions: socioeconomic and emissions projections (five cases), ECS uncertainty (using a common assumed ECS probability distribution), and discount rates (three alternative constant values). Given their climate modeling and projection implications, this section discusses the socioeconomic/emissions and ECS harmonizations. Note that the IWG socioeconomic and emissions and ECS modeling approaches were developed for the IWG's 2010 SCC estimates (Interagency Working Group on the Social Cost of Carbon, 2010) and retained for the 2013 and 2015 estimates (Interagency Working Group on the Social Cost of Carbon, 2013, 2015). The IWG methodology regarding socioeconomic and emissions modeling differs to different degrees from each model's standard structure.

Socioeconomic and emissions variability are considered in the IWG SCC calculations through the five alternative scenarios (USG1 through USG5). Four of the scenarios are described as "baseline" futures assuming negligible greenhouse gas mitigation, and one is described as a "policy" future that stabilizes atmospheric concentrations by 2100 at 550 ppm CO_2-equivalent. Each scenario consists of a set of projections for gross domestic product, population, fossil and industrial CO_2 emissions, land use CO_2 emissions, and non-CO_2 emissions and forcing.

In the IWG methodology, the baseline socioeconomic, emissions, and forcing projections to the year 2100 are drawn from scenario data from the Energy Modeling Forum's 22nd study, EMF 22 (Clarke et al., 2009), which was a multimodel scenario exercise of 10 global IAMs with detailed energy sectors to explore the cost and energy transformation implications of climate targets and international cooperation. The four baseline scenarios are reference "no climate policy" futures associated with 4 of the 10 models participating in the EMF 22 study. The "policy" scenario was derived by the IWG by averaging the 550 ppm CO_2-equivalent scenario results from the same four models, with each variable averaged separately. In the IWG exercise, the SCC estimates resulting from each socioeconomic/emission scenario are given equal weight in the averaging used to derive the overall SCC estimates.

Implementation of these inputs varied somewhat across the three models (see Rose et al., 2014): FUND and PAGE require translation of the projections into model-specific regional population and income; PAGE and DICE use level values, and FUND uses growth rates; and FUND requires derivation of its own fossil and industrial CO_2 emissions in lieu of the standardized projections. In addition, only FUND uses explicit emissions for a subset of non-CO_2 Kyoto greenhouse gases (CH_4, N_2O, SF_6); and DICE and PAGE include non-CO_2 forcing exogenously. To estimate climate damages beyond 2100, the IWG extrapolated the EMF 22-based socioeconomic and emissions inputs from 2100 to 2300.

The IWG approach standardized one climate system modeling assumption, the distribution of the ECS parameter. The IWG calibrated a Roe and Baker (2007) distributional form (see discussion in Chapter 3) to match statements regarding the likelihood of the ECS value made in the IPCC Fourth Assessment Report. Figure 4-2 depicts the chosen calibrated Roe and Baker distribution.[25]



[25]For a detailed discussion, see IWG (2010); also see Box 3-2 in Chapter 3.

FIGURE 4-2 IWG calibrated Roe and Baker ECS distribution.
NOTES: The black line is based on the Roe and Baker (2007) functional form. Additional probability distributions adopted from Figure 9.20 in the source for this figure. The circles below the distributions reflect the median ECS estimate; the ends of the horizontal bars represent the 5th and 95th percentiles of the ECS distributions.
SOURCE: Interagency Working Group on the Social Cost of Carbon (2010, Figure 2).

Role of ECS and Other Assumptions in Determining the Emissions-to-Temperature Link

Projecting global mean surface temperature change from projected emissions in the SCC-IAMs requires sequentially translating emissions trajectories into concentrations, concentrations into radiative forcing, and radiative forcing trajectories into temperature. In the IWG analysis, the ECS parameter is one of several critical parameters governing the last translation from forcing to temperature.

The ECS is a long-standing metric for climate system responsiveness (e.g., Arrhenius, 1896) and is used as an input parameter to most simple climate models, such as those used by the IWG. However, the ECS is not an input parameter to more complex climate models. Rather, it emerges from the behavior of each complex model and is derived as an output based on each model's global mean surface temperature response to a doubling of CO_2 concentrations. The ECS is therefore unique to each model's structure, parameterization, and settings.

The ECS is recognized as an influential parameter in the three IAMs used to calculate the SCC, with studies finding SCC estimates to be relatively sensitive to the assumed ECS (Anthoff and Tol, 2013a, 2013b; Hope, 2013; Butler et al., 2014). This reflects in part the way the ECS is incorporated into these models. Direct comparison of the SCC-IAMs' climate responses has also found that the sensitivity of projected temperature (level and incremental) to the ECS assumptions varies significantly across the three models, with PAGE being the most sensitive and FUND the least sensitive (see Figure 4-3).

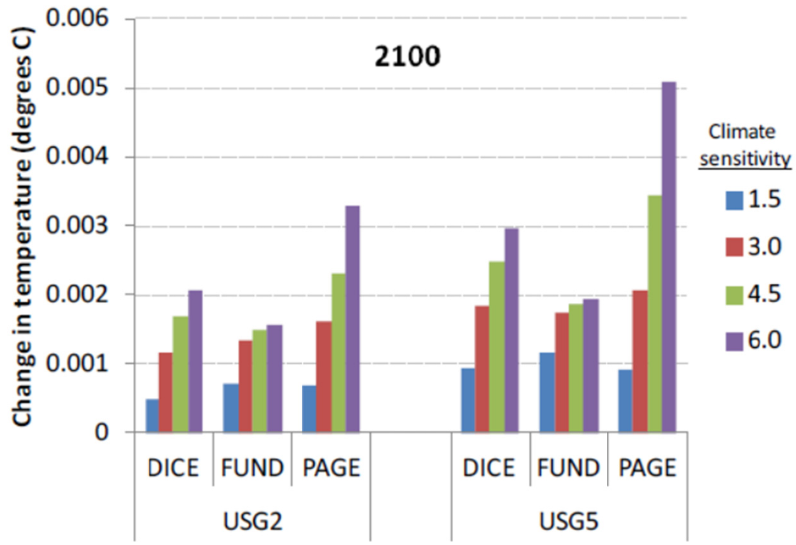


FIGURE 4-3 Projected incremental global mean temperature increase in 2100 of the SCC-IAMs varying the ECS assumption.
NOTES: In DICE, FUND, and PAGE, the increase is in response to a 2020 1 GtC pulse varying the ECS parameter and reference emissions scenario. USG2 and USG5 represent the IWG's highest and lowest emission scenarios, respectively.
SOURCE: Rose et al. (2014, Figure 5-13). Reprinted with permission.

Other climate modeling elements of the three SCC-IAMs, in addition to the ECS, play a significant role in translating emissions into projected global mean temperatures. These include the specifications for the carbon cycle, the ocean response to forcing, non-CO_2 forcing, climate feedbacks, and non-ECS parametric uncertainties. As a result of variations in these specifications across the models, PAGE has slower CO_2 concentration accumulation but higher projected temperatures, FUND has faster accumulation of CO_2 concentrations and higher non-CO_2 forcing but lower projected temperatures, and DICE has CO_2 concentrations and temperature that are the most sensitive to projected emissions. Non-ECS uncertainty also plays a role in FUND and PAGE in defining the distribution of projected temperature.

SENSITIVITY OF THE SCC TO OTHER MODELING ASSUMPTIONS

The committee's charge emphasizes the role of the ECS in estimating the SCC, but the ECS is one of many assumptions that can influence an SCC estimate. Other assumptions include the projected size of the economy and population, emissions levels, discount rate, non-ECS climate parameters, regional temperature downscaling, the assumed sea level rise response rate, and the functional forms and parameterizations for the various climate damages (Anthoff and Tol, 2013a, 2013b; Hope, 2013; Butler et al., 2014; Rose et al., 2014). Some assumptions are potentially more influential than the ECS, as well as interacting with the ECS.

Looking specifically at damages, Anthoff and Tol (2013a, 2013b) identified key sensitivities for FUND SCC estimates in parameters associated with cooling damages, agricultural damages, migration, and energy efficiency improvement. Looking more broadly across the overall PAGE modeling framework, Hope (2013) finds key sensitivities in the model's discounting parameters, climate feedback response, sulfate aerosol effects, and noneconomic damage function exponent and weight parameters. In addition, Butler et al. (2014) illustrate with a modified version of the DICE model the potential importance of interactions between uncertain parameters.

Direct comparison of the model damage components of the three IWG SCC models illustrates the differences in sensitivity of damage estimates to assumed warming levels and the size of the economy. Such comparison finds that PAGE damages are the most sensitive to changes in the level of warming, and FUND damages are the least sensitive. At low levels of warming, DICE and PAGE damages are the most sensitive to changes in the size of the economy, but at high levels of warming, FUND damages are the most sensitive. In both contexts there are warming and income ranges for which there are even differences in the sign of estimated damages, as well as the responsiveness.

These insights suggest that it is important to look beyond the ECS when evaluating current methods and identifying opportunities for improvement. Those opportunities include not only other climatic factors, but also sensitivity to changes in other model inputs and assumptions in other components of the causal chain. There are also uncertainties, and potential sensitivities, associated with elements not currently modeled, including other factors that will drive the physical impacts of global climate change, such as changes in the regional and temporal distribution of precipitation, humidity, changing aerosol and cloud patterns, sea level rise, and potential extreme events.

ASSESSMENT OF SIMPLE CLIMATE MODEL PERFORMANCE

The climate modeling community assesses the performance of its models in two ways: (1) intermodel comparison diagnostics and (2) comparison of projections to historical data. With the exception of some limited intermodel comparison exercises (e.g., Warren et al., 2010; van Vuuren et al., 2011; Rose et al., 2014), similar diagnostics and historical comparisons have not been applied to the simple climate models that serve as inputs to SCC-IAMs calculations.

Simple climate models, such as the ones used in SCC-IAMs, can be assessed through a set of diagnostic experiments described below. The key point of comparison is whether the central projections and ranges of the simple climate models agree with those of more comprehensive Earth system models. These diagnostics should not necessarily disqualify models based on broader responses than the Earth system models, however, as the latter models are known to cluster near central estimates (e.g., Huybers, 2010; Roe and Armour, 2011). Similarly, it is not inappropriate for simple climate models to include feedbacks not represented in Earth system models; but the diagnostics should be run with these additional feedbacks disabled so as to facilitate comparison with more complex models that, because of computational limits, do not include such feedbacks.

Four key properties of any simple climate model can be assessed:

- Transient climate response to emissions (TCRE) can be assessed using extended release experiments along the lines of those conducted by Matthews and Caldeira (2008) or Herrington and Zickfeld (2014). In these experiments, CO_2 is emitted at a constant rate of 20 Gt C/year until such time that cumulative emissions reached 50, 200, 500 or 2000 Gt C, at which point emissions are ceased. The TCRE is given by the ratio of warming to cumulative emissions at the end of the emission period. The TCRE experiments assess the combined response of the climate and the carbon cycle to CO_2 emissions.
- TCR can be assessed with an experiment in which CO_2 concentrations are increased at 1 percent/year from a preindustrial initial value, with the mean warming over years

60-80 defining the TCR. This assesses the multidecade response of climate to CO_2 concentrations, removing from the equation the effects of the carbon cycle and the multicentury adjustments that contribute to ECS.

- The initial pulse-adjustment timescale (IPT) can be assessed with experiments such as that of Joos et al. (2013), in which the temperature response over time to a pulse emission of 100 GtC was assessed relative to a steady-state baseline CO_2 concentration of 389 ppm. Such experiments provide information on both the IPT and the TCRE, but extended release experiments are more relevant to TCRE.
- Finally, the overall baseline response to forcing can be assessed using the representative concentration pathway/extended concentration pathway (RCP/ECP)[26] experiments driven by total forcing (Collins et al., 2013). Specifically, a range of possible forcings can be examined by using the high-emissions 6 RCP/ECP 8.5 and low-emissions RCP/ECP 2.6 pathways. By driving the model directly with climate forcing, these experiments isolate the energy balance portion of the simple climate model.

Although these experiments and this report focus on the climate effect of CO_2 emissions, similar diagnostics can be applied to the simple climate models used in the calculation of the social cost of other climate forcers.

[26]Extended concentration pathways are an extension of representative concentration pathway emissions scenarios from 2100 through 2300 (van Vuuren et al., 2011).

5
Discussions, Conclusions, and Recommendations

The first part of this chapter summarizes the committee's conclusions and presents its recommendation on the first two questions covered in this first phase of the study. The second part of this chapter introduces concepts relevant to the committee's third question and provides conclusions and recommendations on that question.

NEAR-TERM UPDATES TO CLIMATE SYSTEM MODELING IN SCC ESTIMATION

The first two charge questions direct the committee to consider near-term updates to the social cost of carbon (SCC). Specifically, the committee considered whether a near-term update is warranted on the basis of recent evidence regarding the sensitivity of temperature change to carbon emissions. The basic issues are the technical merits and challenges of a narrowly focused update to the SCC estimates and whether the Interagency Working Group on the Social Cost of Carbon (IWG) should conduct a near-term update of the SCC prior to receiving recommendations related to a more comprehensive update (Phase 2 of the committee's study).

In its analysis, the committee considered the criteria outlined in Chapter 1, including

- the accuracy and characterization of uncertainty of climate system modeling (e.g., assessing whether a near-term update would necessarily improve the representation of the response of temperature change to emissions relative to more complete, state-of-the-art models of the climate system);
- overall SCC reliability;
- alternative options for climate system representation; and
- whether there is sufficient benefit to warrant investing limited available resources in conducting a near-term update to the SCC estimates, relative to investing those resources in lasting improvements to the methods and science underlying the SCC.

CONCLUSION 1 The equilibrium climate sensitivity (ECS) is only one parameter affecting the social cost of carbon (SCC). Each of the three SCC integrated assessment models also embodies a different representation of the climate system and its underlying uncertainties, including relationships and parameters beyond the ECS. Therefore, updating the ECS alone within the current SCC framework may not significantly improve the estimates.

CONCLUSION 2 The relationship between CO_2 emissions and global mean surface temperature can be summarized by four metrics: equilibrium climate sensitivity (ECS), transient climate response, transient climate response to emissions, and the initial pulse-adjustment timescale. ECS is less relevant than the other three metrics in characterizing the climate system response on timescales of less than a century. As a long-term, equilibrium metric, ECS alone does not provide an adequate summary of the relationship between CO_2 emissions and global mean surface temperature for calculating the social cost of carbon (SCC). Therefore, simply

updating the distribution of ECS without assessing the impact on these other metrics may not result in an improved estimate of the SCC.

RECOMMENDATION 1 The committee recommends against a near-term update to the social cost of carbon based simply on a recalibration of the probability distribution of the equilibrium climate sensitivity (ECS) to reflect the recent consensus statement in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Consequently, the committee also recommends against a near-term change in the distributional form of the ECS.

Rather than updating the ECS in the current framework, the IWG could undertake efforts to adopt or develop a common "module" that represents the relationship between CO_2 emissions and global mean surface temperature change, its uncertainty, and its profile over time. If the IWG pursues such an effort, the following criteria would provide a more robust alternative to assessing the link between CO_2 emissions to temperature change than ECS alone:

1. The module's behavior should be consistent with the best available scientific understanding of the relationship between emissions and temperature change, its pattern over time, and its uncertainty. Specifically, the module should be assessed on the basis of both its response to a pulse of emissions and its response to long-term forcing trajectories (specifically, trajectories designed to assess transient climate response and transient climate response to emissions, as well as high- and low-emissions baseline trajectories). Given the degree of assessment they face, including consistency with observational data, the IPCC-class Earth system models provide a reference for evaluating the central projections of a climate module.
2. The proposed module should strive for simplicity and transparency so that the central tendency and range of uncertainty in its behavior are readily understood, are reproducible, and are amenable to continuous improvement over time through the incorporation of evolving scientific evidence.
3. The possible implications of the choice of a common climate module for the assessment of impacts of other, non-CO_2 greenhouse gases should also be considered.

NEAR-TERM ENHANCEMENT OF THE QUALITATIVE CHARACTERIZATION OF SCC UNCERTAINTY TO INCREASE TRANSPARENCY

The third charge question directs the committee to consider ways to enhance the qualitative characterization of uncertainties associated with the current SCC estimates in the near term to increase the transparency associated with using these estimates in regulatory impact analyses.

To be well defined, the SCC must be conditioned on certain variables, for example, the year in which the change in emissions is assumed to occur. Parameters that may require policy or value judgments must also be specified: these may concern how effects across people are aggregated, including across time, across different income levels, and over political jurisdictions. The SCC may be presented on the basis of different assumed values for such parameters, but it is generally inappropriate to take averages across such values because the variation does not reflect—or does not *only* reflect—uncertainty. For practical regulatory purposes, for example, it is necessary to present SCC estimates conditional on alternative discount rates in order to allow those SCC estimates to be combined with other cost and benefit estimates that use different discount rates.

The SCC depends on a number of inputs that are uncertain. Some are aspects of the natural world, such as the sensitivity of temperature change to emissions and how it evolves over time. Others are consequences of current and future human behavior, such as population growth, economic growth, and the trajectory of global greenhouse gas emissions. For regulatory decision making, it is at least conceptually possible to describe the uncertainty of these inputs in SCC calculations using probability distributions. Ideally, joint probability distributions could be defined for all of the uncertain inputs to an SCC-IAM, and the impact of uncertainty on the SCC could be evaluated using Monte Carlo analysis or a related approach.

One reason for modeling uncertainty is related to nonlinearities. If the SCC calculation involves nonlinearities over the range of uncertain parameters, the average value of the SCC computed from random draws of these uncertain inputs may not be the same as the single SCC computed from the average parameter values. The implications of such nonlinearities may be difficult to know a priori, suggesting it is best to compute the SCC from random draws of uncertain inputs.

It is also important to model uncertainty in order to provide a range of plausible estimates for cost-benefit analysis. The U.S. Office of Budget and Management (OMB) Circular A-4 requests a formal quantitative analysis of uncertain costs and benefits for major rules with effects of $1 billion or more. Given the consequences of the presence of CO_2 emissions across many government rulemakings, it is important to address this need.

Handling of Uncertainty in IWG Analysis

In constructing the SCC, the IWG treated some parameters of the climate system and damage functions as uncertain and random and represented these parameters using probability distributions. A common distribution, using a distributional form developed by Roe and Baker (2007), was used to represent the ECS in each of the three SCC-IAMs: the Dynamic Integrated Climate-Economy Model (DICE), the Policy Analysis of the Greenhouse Effect (PAGE), and the Climate Framework for Uncertainty, Negotiation and Distribution (FUND). In addition, 11 climate system parameters in FUND and 10 in PAGE were also represented by probability distributions, as were 50 parameters in FUND's damage model and 46 in PAGE's damage model (see Chapter 2 for an overview of these models). Socioeconomic and emissions uncertainty was also considered through five alternative scenarios. In calculating the SCC, each SCC-IAM was run by taking 10,000 draws from the relevant probability distributions and calculating the SCC for each draw, conditional on a socioeconomic and emissions scenario and discount rate.

CONCLUSION 3 The Interagency Working Group on the Social Cost of Carbon (SCC) technical support document explicitly describes the factors on which the SCC is conditioned, such as the year emissions occur and the discount rate and also makes explicit the sources of distributions for various inputs. However, it does not detail all sources of model-specific uncertainty in the social cost of carbon integrated assessment models.

RECOMMENDATION 2 When presenting the social cost of carbon (SCC) estimates, the Interagency Working Group (IWG) on the SCC should continue to make explicit the sources of uncertainty. The IWG should also enhance its efforts to describe uncertainty by adding an appendix to the technical support document that

describes the uncertain parameters in the Climate Framework for Uncertainty, Negotiation and Distribution and Policy Analysis of the Greenhouse Effect models.

CONCLUSION 4 Multiple runs from three models provide a frequency distribution of the social cost of carbon (SCC) estimates based on five socioeconomic-emissions scenarios, three discount rates, draws from the equilibrium climate sensitivity distribution, and other model-specific uncertain parameters. This set of estimates does not yield a probability distribution that fully characterizes uncertainty about the SCC.

Sources of Uncertainty Omitted from the IWG Analysis

The committee notes that none of the three SCC-IAMs (nor any others of which the committee is aware) are sufficiently comprehensive to include all of the uncertainties in the inputs that are likely to be important in calculating the SCC. Moreover, explicit distributions for some important inputs (e.g., emission scenarios, economic growth, and population) have not been developed by the IWG for use in estimating the SCC. Factors omitted or not adequately captured by the analysis need to be better characterized. In addition, a single unifying discussion of captured and omitted uncertainty is needed. There is, however, no section of the IWG's technical support documents that contain a unified discussion of this topic.

RECOMMENDATION 3 The Interagency Working Group on the Social Cost of Carbon (IWG) should expand its discussion of the sources of uncertainty in inputs used to estimate the social cost of carbon (SCC), when presenting uncertainty in the SCC estimates. The IWG should include a section entitled "Treatment of Uncertainty" in each technical support document updating the SCC. This section should discuss various types of uncertainty and how they were handled in estimating the SCC, as well as sources of uncertainty that are not captured in current SCC estimates.

The uncertainties discussed in this section would include the uncertain parameters unique to each of the models, uncertainty about climate change impacts and their valuation, and the risk of potential catastrophic outcomes. The section would also discuss the implicit, equal weight placed on the three IAMs and five socioeconomic scenarios in computing an average SCC, the possible alternatives of unequal weights or alternative models and scenarios, and the motivation for the chosen approach. The executive summary of the technical support document and individual regulatory impact analyses that use the SCC might usefully provide a summary of this discussion.

Reporting of Results

In the executive summaries of the IWG's technical support documents, the presentation of SCC estimates and the description of the uncertainty underlying them are brief. For each year of interest, four summary estimates of the SCC are shown (see Table 2-3, in Chapter 2): the average SCC for 2.5, 3, and 5 percent discount rates, as well as the 95th percentile for a 3 percent discount rate.[27] Thus, the only range of SCC estimates presented in the executive summary of the technical support documents is the range based on discount rates, together with the 95th percentile of the SCC based on a 3 percent discount rate. A more complete characterization of uncertainty would include other sources of variability in the SCC, for each discount rate, and would include both high and low values. These values could be used in sensitivity analyses in regulatory impact analyses.

CONCLUSION 5 It is important to continue to separate the impact of the discount rate on the social cost of carbon from the impact of other sources of variability. A balanced presentation of uncertainty includes both low and high values conditioned on each discount rate.

RECOMMENDATION 4 The executive summary of each technical support document should provide guidance concerning interpretation of reported social cost of carbon (SCC) estimates for cost-benefit analysis. In particular, the guidance should indicate that SCC estimates conditioned on a particular discount rate should be combined with other cost and benefit estimates conditioned on consistent discount rates, when they are used together in a particular analysis.

The guidance should also indicate that when uncertainty ranges are presented in an analysis, those ranges should include uncertainty derived from the frequency distribution of SCC estimates. To facilitate such inclusion, the executive summary of the technical support document should present symmetric high and low values from the frequency distribution of SCC estimates with equal prominence, conditional on each assumed discount rate.

One approach to the implementation of this recommendation would be to present in the executive summary a table similar to Table 5-1 below which would show high and low estimates of the SCC, as well as the average estimate, for each discount rate. The executive summary could also display the frequency distribution of SCC estimates as in Figure 5-1, with separate graphs for each discount rate. Separating the presentation of frequency distributions will encourage careful attention to the special role of discount rates on the basis of the regulatory context and the need to combine the SCC with other cost and benefit estimates. Also, the IWG could identify a high percentile (e.g., 90th, 95th) and corresponding low percentile (e.g., 10th, 5th) of the SCC frequency distributions on each graph. This approach would define a usable uncertainty range for the regulatory impact analysis for each discount rate.

[27]The most recent IWG technical support document states (Interagency Working Group on the Social Cost of Carbon, 2015, p. 2): “Three values are based on the average SCC from three integrated assessment models (SCC-IAMs), at discount rates of 2.5, 3, and 5 percent. The fourth value, which represents the 95th percentile SCC estimate across all three models at a 3 percent discount rate, is included to represent higher-than-expected impacts from temperature change further out in the tails of the SCC distribution.”

TABLE 5-1: An Example of a Table of SCC Estimates

	Discount Rate								
Year		5.00%			3.00%			2.50%	
	Low	Avg.	High	Low	Avg.	High	Low	Avg.	High
2020	--	--	--	--	--	--	--	--	--
2025	--	--	--	--	--	--	--	--	--
…									
2050	--	--	--	--	--	--	--	--	--

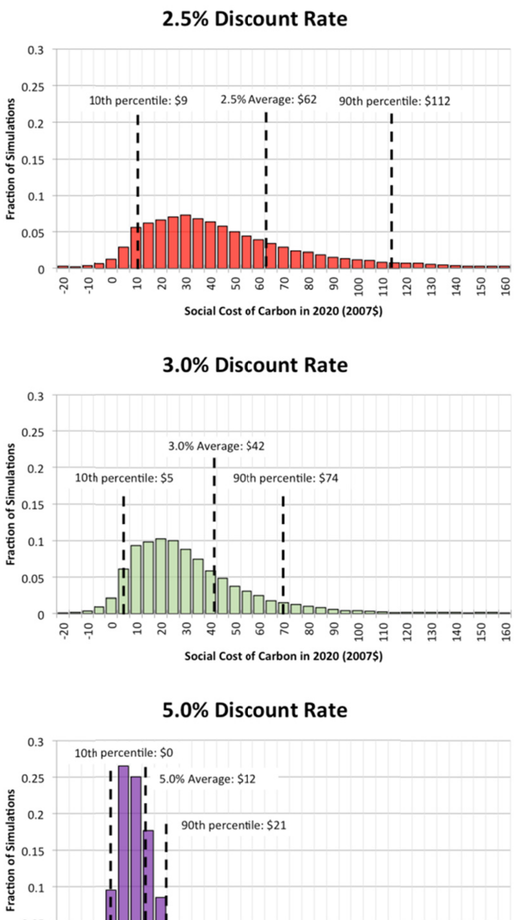


FIGURE 5-1 Examples of the frequency distribution of SCC estimates for 2020 (in 2007 dollars per metric ton of CO_2).

NOTES: The 10th and 90th percentiles of the SCC estimates are identified only as an example for presentation. The frequency distributions shown represent most of the 150,000 SCC estimates. However, they do not represent the entire distribution. Some estimates fall outside the range of the horizontal axis shown.

SOURCE: Developed from IWG SCC estimates provided to the committee by the U.S. Environmental Protection Agency.

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Appendix A
Biographical Sketches of Committee Members and Staff

MAUREEN L. CROPPER (*Cochair*) is a distinguished university professor and chair of the Department of Economics at the University of Maryland. She is also a senior fellow at Resources for the Future and a research associate of the National Bureau of Economic Research. Previously, she was a lead economist at the World Bank. Her research has focused on valuing environmental amenities (especially environmental health effects), on the discounting of future health benefits, and on the tradeoffs implicit in environmental regulations. Her current research focuses on energy efficiency in India, on the impact of climate change on migration, and on the benefits of collective action in pandemic flu control. She has served as chair of the Economics Advisory Committee of the Science Advisory Board of the U.S. Environmental Protection Agency and as past president of the Association of Environmental and Resource Economists. She is a member of the National Academy of Sciences. She has a B.A. in economics from Bryn Mawr College and a Ph.D. in economics from Cornell University.

RICHARD G. NEWELL (*Cochair*) is the Gendell professor of energy and environmental economics at Duke University's Nicholas School of the Environment and director of the Duke University Energy Initiative. Previously, he served as the administrator of the U.S. Energy Information Administration and as the senior economist for energy and environment on the President's Council of Economic Advisers. He is on the board of directors of Resources for the Future, a research associate of the National Bureau of Economic Research, and a member of the North Carolina Energy Policy Council. His work has covered the economics of markets and policies for energy, the environment, and related technologies, including energy systems forecasting, market-based policy, energy efficiency, discounting, and incentives for technological innovation and adoption. He has a B.S. and a B.A. from Rutgers, an M.P.A. from the Woodrow Wilson School of Public and International Affairs at Princeton University, and a Ph.D. from Harvard University.

MYLES ALLEN is professor of geosystem science in the Environmental Change Institute in the School of Geography and the Environment and in the Department of Physics, both at the University of Oxford. His research focuses on how human and natural influences on climate contribute to observed climate change and extreme weather events. He founded climateprediction.net and weatherathome.org experiments, using volunteer computing for weather and climate research. His recent work has dealt with quantifying the cumulative impact of carbon dioxide emissions on global temperatures and on the implications of reframing climate change as a carbon stock problem. He has served on several working groups on the physical science assessments of the Intergovernmental Panel on Climate Change and on the core writing team of the synthesis report in 2014. He was awarded the Appleton Medal from the Institute of Physics in 2010. He has a doctorate in physics from the University of Oxford.

MAXIMILIAN AUFFHAMMER is the George Pardee Jr. professor of international sustainable development and associate dean of interdisciplinary studies at the University of California at Berkeley. His research focuses on environmental and resource economics, energy economics, and applied econometrics. He is a research associate at the National Bureau of Economic Research in the Energy and Environmental Economics group, a Humboldt Fellow, and a lead author for the Intergovernmental Panel on Climate Change (IPCC). He is a recipient of the Cozzarelli Prize awarded by the *Proceedings of the National Academy of Sciences* and of the

Campus Distinguished Teaching Award and the Sarlo Distinguished Mentoring Award from the University of California at Berkeley. He has a B.S. in environmental science and an M.S. in environmental and resource economics from the University of Massachusetts at Amherst and a Ph.D. in economics from the University of California at San Diego.

CHRIS E. FOREST is associate professor of climate dynamics in the Departments of Meteorology and Geosciences, an associate in the Earth and Environmental Systems Institute, and associate director for the Network for Sustainable Climate Risk Management, all at Pennsylvania State University. He studies how to characterize uncertainties in climate projections from global to regional scales and understanding how these uncertainties should be included in climate change decision analyses. He served as a lead author on the Intergovernmental Panel on Climate Change chapter on the evaluation of climate models and as a lead author on a Climate Change Science Program synthesis and assessment report examining atmospheric and surface temperature trends. He serves on the leadership team for the Atmospheric and Hydrospheric Sciences Section of the American Association for the Advancement of Science. He has a B.S. in applied math, engineering, and physics from the University of Wisconsin-Madison and a Ph.D. in meteorology from the Massachusetts Institute of Technology.

INEZ Y. FUNG is a professor of atmospheric sciences at the University of California at Berkeley. She is also a member of the science team for NASA's Orbiting Carbon Observatory. She studies the interactions between climate change and biogeochemical cycles, particularly the processes that maintain and alter the composition of the atmosphere. Her research emphasis is on using atmospheric transport models and a coupled carbon-climate model to examine how CO_2 sources and sinks are changing. She is a recipient of the American Geophysical Union's Roger Revelle Medal. She is a member of the National Academy of Sciences, and a fellow of the American Meteorological Society, the American Geophysical Union, the American Academy of Arts and Sciences, and the American Philosophical Society. She has a S.B. in applied mathematics and a Sc.D. in meteorology from the Massachusetts Institute of Technology.

JAMES K. HAMMITT is professor of economics and decision sciences at the T.H. Chan School of Public Health and director of the Center for Risk Analysis, both at Harvard University, and an affiliate of the Toulouse School of Economics. His research concerns the development and application of quantitative methods—including benefit-cost, decision, and risk analysis—to health and environmental policy. Topics include management of long-term environmental issues with important scientific uncertainties, such as global climate change and stratospheric-ozone depletion, evaluation of ancillary benefits and countervailing risks associated with risk-control measures, and characterization of social preferences over health and environmental risks using revealed-preference, stated-preference, and health-utility methods. He has a Ph.D. in public policy from Harvard University.

HENRY D. JACOBY is the William F. Pounds professor of management (emeritus) in the Sloan School of Management and former codirector of the Joint Program on the Science and Policy of Global Change, both at the Massachusetts Institute of Technology (MIT). His work has focused on the integration of the natural and social sciences and policy analysis in application to the threat of global climate change. Previously, he served on the faculties of the Department of Economics and the Kennedy School of Government, both at Harvard University. He has also served as director of the Harvard Environmental Systems Program, director of the

MIT Center for Energy and Environmental Policy Research, associate director of the MIT Energy Laboratory, and chair of the MIT faculty. He has an undergraduate degree in mechanical engineering from the University of Texas at Austin and a Ph.D. in economics from Harvard University.

JENNIFER A. HEIMBERG (*Study Director*) is a senior program officer in the Division of Earth and Life Sciences (DELS) and the Division of Behavioral and Social Sciences and Education. In her work for the Nuclear and Radiation Studies Board in DELS, she has focused on nuclear security, nuclear detection capabilities, and environmental management issues, and she has directed studies and workshops related to nuclear proliferation, nuclear terrorism, and the management of nuclear wastes. Previously, she worked as a program manager at the Johns Hopkins University Applied Physics Laboratory, where she established its nuclear security program with the Department of Homeland Security's Domestic Nuclear Detection Office. She has a B.S. in physics from Georgetown University, a B.S.E.E. from Catholic University, and a Ph.D. in physics from Northwestern University.

ROBERT KOPP is associate director of Rutgers Energy Institute and an associate professor in the Rutgers University Department of Earth & Planetary Sciences. His research focuses on understanding uncertainty in past and future climate change, with major emphases on sea level change and on the interactions between physical climate change and the economy. He is a contributing author to the working groups on physical science and on impacts, adaptation, and vulnerability of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. He is a Leopold Leadership fellow and a recipient of the Sir Nicholas Shackleton Medal of the International Union for Quaternary Research and the William Gilbert Medal of the American Geophysical Union. He has an undergraduate degree from the University of Chicago and a Ph.D. in geobiology from the California Institute of Technology.

WILLIAM PIZER is a professor in the Sanford School of Public Policy and faculty fellow at the Nicholas Institute for Environmental Policy Solutions at Duke University. His current research examines how public policies to promote clean energy can effectively leverage private-sector investments, how environmental regulation and climate policy can affect production costs and competitiveness, and how the design of market-based environmental policies can be improved. Previously, he was Deputy Assistant Secretary for Environment and Energy at the U.S. Department of the Treasury, overseeing the department's role in the domestic and international environment and energy agenda of the United States. He was also a researcher at Resources for the Future in Washington, D.C. He has a bachelor's degree in physics from the University of North Caroling at Chapel Hill and a master's degree and a Ph.D. in economics from Harvard University.

STEVEN ROSE is a senior research economist in the Energy and Environmental Research Group at the Electric Power Research Institute. His research focuses on long-term modeling of energy systems and climate change drivers, mitigation, and potential climate risks and responses, as well as the economics of land use and bioenergy as they relate to climate change and energy policy. He serves on the U.S. government's Carbon Cycle Scientific Steering Group and Environmental Protection Agency's Science Advisory Board panel on biogenic carbon dioxide emissions accounting. He was also a lead author for the Fifth and Fourth Assessment Reports of the Intergovernmental Panel on Climate Change and for the U.S. National Climate Assessment.

He has a B.A. in economics from the University of Wisconsin-Madison and a Ph.D. in economics from Cornell University.

RICHARD SCHMALENSEE is the Howard W. Johnson professor of management (emeritus) and professor of economics (emeritus) at MIT. Previously, at MIT, he was the John C. Head III dean of the Sloan School of Management, director of the Center for Energy and Environmental Policy Research, and a member of the Energy Council. He also previously served as a member of the President's Council of Economic Advisers. His research and teaching have focused on industrial organization economics and its applications to business decision making and public policy. He is a fellow of the Econometric Society and of the American Academy of Arts and Sciences. He has served on the executive committee of the American Economic Association and as a director of several corporations, and he is currently chair of the board of Resources for the Future. He was a distinguished fellow of the Industrial Organization Society. He has an S.B. and a Ph.D. in economics from the Massachusetts Institute of Technology.

JOHN P. WEYANT is professor of management science and engineering, director of the Energy Modeling Forum, and deputy director of the Precourt Institute for Energy Efficiency, all at Stanford University. His current research focuses on analysis of global climate change policy options, energy efficiency analysis, energy technology assessment, and models for strategic planning. He has been a convening lead author or lead author for several chapters of the IPCC reports, and, most recently, as a review editor for the climate change mitigation working group of the IPCC's Fourth and Fifth Assessment Reports. He was also a founder and serves as chair of the Scientific Steering Committee of the Integrated Assessment Modeling Consortium, a collaboration of 53 member institutions from around the world. He is a recipient of the Adelmann-Frankel award from the U.S. Association for Energy Economics for unique and innovative contributions to the field of energy economics. He has a B.S./M.S. in aeronautical engineering and astronautics and M.S. degrees in engineering management and in operations research and statistics from Rensselaer Polytechnic Institute and a Ph.D. in management science with minors in economics, operations research, and organization theory from the University of California at Berkeley.

CASEY J. WICHMAN (*Technical Consultant*) is a fellow at Resources for the Future in Washington, D.C. His research is concentrated at the intersection of environmental and public economics, with an emphasis on examining the ways individuals make decisions in response to environmental policies using quasi-experimental techniques. In particular, his work analyzes the effectiveness of price and nonprice interventions for water conservation, the role of information in the design of environmental policy, and the effect of water scarcity in the energy sector. He has a B.A. in economics from Ithaca College, an M.S. from North Carolina State University, and an M.S. and a Ph.D. in agricultural and resource economics from the University of Maryland at College Park.

Appendix B

Open Meeting Agenda

First Meeting
Committee on Assessing Approaches to Updating the Social Cost of Carbon

Room 208
Keck Center
500 5th St., NW
Washington, DC 20001

Wednesday, September 2, 2015
OPEN SESSION (open to the public)

9:30 Welcome Introductions
MaryEllen O'Connell, Interim Director, Board on Environmental Change and Society
Maureen Cropper and Richard Newell, Cochairs
Marisa Gerstein Pineau, Program Officer

9:45 Presentation: Sponsors' Interests and Goals for the Study
Ken Gillingham, Council of Economic Advisers
Q&A: **Richard Newell and Maureen Cropper**, Moderators

10:45 *Break*

11:15 Presentation: Methodology for the Social Cost of Carbon Estimates
Elizabeth Kopits, U.S. Environmental Protection Agency
Q&A: **Richard Newell and Maureen Cropper**, Moderators

12:45 Closing Remarks
Maureen Cropper and Richard Newell, Co-Chairs

1:00 Adjourn Open Session