Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis

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Workshop Report:

Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis – Part 1

Modeling Climate Change Impacts and Associated Economic Damages

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I. Introduction

This report summarizes the November 18-19, 2010 workshop, *Modeling Climate Change Impacts and Associated Economic Damages*, sponsored by the U.S. Environmental Protection Agency (EPA) and U.S. Department of Energy (DOE). This was the first in a series of two workshops, titled *Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis.*

This report is organized as follows:

- The first section provides an introduction to the report and the workshop, including context and workshop format.
- The second section provides a summary of the potential future improvements to climate change integrated assessment models identified by workshop participants. This section aims to summarize, categorize, and organize the wide variety of recommendations highlighted by individual participants over the course of the two-day workshop.
- The third section provides a chronological presentation of the workshop proceedings, including a summary of each presentation, question and answer session, and discussion section.
- The appendix to the report provides the final workshop agenda with charge questions, the participant list, and extended abstracts of most speaker presentations.

This report serves as the EPA and DOE planning committee's summary of the workshop. It has not received official endorsement from the workshop speakers and other participants.

Context

In 2009 and early 2010, EPA and DOE participated in the interagency working group on the social cost of carbon (SCC). The interagency group used the DICE, FUND, and PAGE integrated assessment models (IAM) to estimate a range of values for the social cost of carbon from 2010 to 2050 for use in U.S. government regulatory impact analyses (RIA). The SCC working group reported their findings in February 2010 and the estimated SCC values were first used in the analysis of DOE's Energy Conservation Standard for Small Electric Motors.[1] In preparation for future iterations of this process, EPA and DOE seek to improve the natural science and economic understanding of the potential impacts of climate change on human well-being.

To help motivate and inform this process, EPA's National Center for Environmental Economics (NCEE) and Office of Air and Radiation's (OAR) Climate Change Division and DOE's Office of Climate Change Policy and Technology sponsored a pair of invitational workshops in late 2010 and early 2011. The first workshop took place on November 18-19, 2010 and focused on conceptual and methodological issues related to modeling and valuing climate change impacts. It also addressed implications of these estimates for policy analysis. The second workshop, to be held January 27-

[1] See http://go.usa.gov/3fH.

28, 2011, will review the quantitative research that examines the physical impacts and economic damages for a variety of impact categories (e.g., agriculture, human health, ocean acidification). These workshops are intended to inform future refinements of the SCC and ongoing work of the U.S. government to improve regulatory assessment and policy analysis.

Workshop Format

The workshop took place over two days, November 18-19, 2010, at the Omni Shoreham Hotel in Washington, DC. The workshop was attended by approximately 110 individuals, including representatives from several U.S. federal government agencies, non-governmental organizations, academia, and the private sector. A full list of workshop participants is available in the Appendix.

The workshop opened and concluded with remarks by representatives of EPA and DOE. After an initial background talk on the interagency SCC process, the workshop consisted of four plenary sessions:

- Session 1: Overview of Existing Integrated Assessment Models
- Session 2: Near-Term DOE and EPA Efforts
- Session 3: Critical Modeling Issues in Assessment and Valuation of Climate Change Impacts
- Session 4: Implications for Climate Policy Analysis and Design

Each session included a panel of speakers who gave presentations, responded to questions specific to their talk, and participated in an open discussion with the audience at the end of each session. The full workshop agenda, charge questions, and extended abstracts of most presentations are available in the Appendix.

II. Potential Future Improvements Suggested by Workshop Participants

Over the course of the two-day workshop, a number of suggestions for improving the assessment and valuation of climate change impacts were identified by the workshop participants. These suggestions are related to ways that both integrated assessment modeling generally and SCC estimation specifically could be improved in the future. This section aims to summarize and categorize those suggestions.

The section is organized into four categories of comments:

- overarching comments;
- comments related to the modeling of natural systems in IAMs;
- comments related to the modeling of human systems in IAMs; and
- comments related to the communication of IAM results.

The potential improvements outlined below represent the perspectives of one or more participants but, importantly, do not represent a consensus since none was sought at this workshop.

Overarching comments

Throughout the course of the workshop, many participants made general comments related to the discipline of climate policy analysis and specific suggestions for potential future improvements related to the underlying structure of and inputs to integrated assessment models. These comments spanned a wide range of topics, include the following:

- **Improve both aggregated and disaggregated models while highlighting the strengths of each.** There was considerable debate about the appropriate level of disaggregation and the merits of using more or less aggregated models for different types of applications. Several participants suggested that increased attention to disaggregation was important to understanding the true impacts associated with climate change. However, some were skeptical of current capabilities to downscale global climate models (GCMs) to produce reliable disaggregated estimates of impacts, at local or regional scales. In the end many participants suggested that a two-track approach is necessary and that there are important roles for models across the spectrum of aggregation.

    - ***Build better disaggregated models.*** Many conference participants recommended using more disaggregated models, emphasizing that aggregation can contribute to a bias in impact estimates. (For example, if damages increase at an increasing rate with higher local temperatures, then using regionally averaged temperature increases would underestimate the average local damages.) They recommended that models increase disaggregation spatially and sectorally to allow for more realistic representations of impact mechanisms. They also emphasized the need to explicitly model the temporal and spatial variability of climate impacts.

    - ***Better inform calibration of aggregated models with disaggregated models.*** Some participants suggested using more disaggregated models to help inform calibration of more aggregated models. Several noted it is possible to incorporate more realistic impact mechanisms in disaggregated models, and to more accurately parameterize such models using empirical data. Participants suggested that the predictions of more disaggregated models might be useful to calibrate components of the more general and comprehensive aggregated models (at least within the range of temperature changes observed in the data).

- **Increase model flexibility to facilitate improvements.** Several participants suggested that IAMs should be (re)designed to be more flexible so that it is easier to update the models or model components to incorporate new research findings. At least two participants suggested moving to a more modular structure where different components could easily be updated or replaced by newer modules as research develops. For example, increased modularity could allow researchers to replace sector-specific damage functions when new research points to different parameter values or functional forms. While IAMs, which link climate models to impact and economic models, are somewhat modular in theory, this has not always been the case in practice. Modularity could be introduced in model implementation in multiple ways. A simple

effort might be to ensure interoperability between existing models of physical impacts and economic damages and various climate system modules. A more complex effort might allow researchers to focus in on one specific aspect of the problem without affecting compatibility with the system.

- **Conduct new empirical studies and better incorporate existing research.** Participants noted repeatedly that IAMs need new primary research on impacts from which to draw. Participants specifically highlighted a need for empirical studies on: physical impacts; monetization of damages; decision making under uncertainty; adaptation-related technological change; adaptive capacity; response-time, recovery, and cost related to disasters; tipping points; and impacts beyond 2050. Participants also noted that IAMs could be improved by drawing more on the existing body of research. Some participants suggested that assessments of climate change impacts under high-end warming scenarios would help the integrated assessment modelers calibrate their damage functions over ranges of temperatures higher than those typically examined in climate damage assessment studies based on historical data.

- **Develop more robust long-term projections of inputs.** Several participants emphasized the need to develop and employ a more complete set of multi-century projections for socio-economic and climate inputs, in particular projections of population, GDP, and greenhouse gas emissions that more fully characterize the uncertainty of such long term forecasts. A standardized set of probabilistic long-term socio-economic projections could be used as a substitute for, or complement to, the traditional scenario-based approach as exemplified by the IPCC Special Report on Emissions Scenarios (SRES).[2]

- **More fully incorporate uncertainty**. Several participants emphasized the need to more fully account for uncertainty at all stages in the modeling process from model inputs and parameters to outputs, using fat-tailed distributions where appropriate. This includes parametric, stochastic, and structural uncertainty. Participants argued that many of the current inputs and damage parameters represent too narrow a range of possibilities. Throughout the conference, speakers and participants identified the need to more fully account for the complex and non-linear implications at the high ends of the climate change impacts probability distribution.

- **Identify metrics for model validation.** Several participants highlighted the need to identify metrics and methods of validation to provide an assessment of models and model results. These participants argued that without metrics for validation, there is no indication of how well a model is performing or to what degree the results are accurate.

- **Increase communication between natural scientists and economists.** Numerous conference participants and speakers raised the need to increase the communication between natural scientists and economists in order to facilitate and build a collaborative community.

[2] http://www.ipcc.ch/ipccreports/sres/emission/index.htm

- **Increase funding for climate economics and integrated assessment research**. Throughout the workshop, participants repeatedly highlighted the currently insufficient level of funding needed to robustly estimate economic damages of climate change and the SCC. Participants underscored the large discrepancy between levels of funding for natural science research and comparatively low levels of funding for economic valuation and integrated assessment research. Several participants also noted that relatively few researchers are currently working in the field of climate change economics and valuation. Therefore, the existing body of research in this field is relatively thin compared to other areas of climate change science.

Comments related to the modeling of natural systems in IAMs

Participants also suggested potential future improvements related to the modeling of natural systems in IAMs. These suggestions include the following:

- **Capture climate variables beyond global mean temperature.** Several participants emphasized the importance of developing more explicit, comprehensive, and detailed characterizations of the climate variables and threshold effects. Specifically, numerous participants highlighted the need for climate variables other than global mean temperature (e.g., precipitation, storms, seasonal and diurnal temperature variations, the rate of temperature change, etc.) to drive impacts. Participants noted that a better characterization of these climate variables on a disaggregated scale would provide opportunities for improved model calibration.

- **Incorporate the co-variance between climate sensitivity and transient climate response.** A few presenters emphasized the importance of accounting for the co-variance between climate sensitivity and transient climate response, especially in probabilistic models that consider a wide range of possible equilibrium climate sensitivity values (e.g., Baker and Roe 2009). Some participants also highlighted the importance of explicitly modeling relationships between the strength of the non-CO_2 forcing, climate sensitivity, and ocean heat capacity. High equilibrium climate sensitivity is correlated with a more strongly negative current aerosol forcing (and thus moderately negative total non-CO_2 forcing). It is also correlated with a higher ocean heat capacity and a longer timescale to reach equilibrium. As a result of the relationship between equilibrium climate sensitivity and ocean heat capacity, the probability distribution for the transient climate response is narrower and has less of a 'fat tail' than the distribution for equilibrium climate sensitivity.

Comments related to the modeling of human systems in IAMs

Many participants made suggestions of potential future improvements related to modeling of human systems in IAMs. These suggestions include the following:

- **Consider alternative functional forms for damage functions.** Numerous conference participants highlighted the need to re-evaluate the functional form of the models' damage representations. The suggested improvements included: evaluating whether impacts should be

additive or multiplicative[3]; better incorporating discontinuities; making damage functions more reactive to extreme temperature increases; and generally considering a broader set of functional forms for damage functions. It is important to consider alternative functional forms given the challenges in extrapolating damage functions calibrated at 2-3 °C global warming to considerably higher global average temperature increases.

- **Better incorporate welfare and equity.** Workshop participants identified numerous potential improvements related to welfare and equity.

    - Many participants argued that the formulation of welfare functions should be reconsidered and refined. Some participants further argued that consumption alone was not a good measure of welfare, suggesting that more robust measures be used instead. For example, participants suggested that multivariate utility functions be used, in order to better account for a variety of goods valued by consumers. These functions could combine consumption of market and non-market goods such as manufactured goods and environmental amenities.

    - Although discounting was not on the workshop agenda, numerous participants emphasized the need to re-evaluate discounting assumptions in SCC estimates. Some participants suggested that discounting be made endogenous to the models and related to economic growth. Some participants suggested incorporating distributional considerations into discounting.

    - Several workshop participants suggested that models incorporate distributional equity in ways other than through discounting. For example, this could be done by equity weighting the estimated monetized damages in each region before aggregating to the global scale. Some emphasized that ignoring the curvature of utility functions means that negative impacts on poor countries are equivalent to those in well developed countries.

    - Several workshop participants suggested that risk aversion was not properly incorporated into the models. These participants suggested that assumptions about risk aversion should be re-evaluated and refined.

- **Incorporate natural capital.** Several workshop participants suggested that natural capital be better incorporated into IAMs. In particular, participants emphasized the importance of capturing the imperfect substitution between natural and human-made physical capital.

- **Incorporate more sectors.** Many participants suggested that current IAMs do not include all impacted sectors. For example, no IAMs currently represent damages from ocean acidification. They indicated that improvements could be made by incorporating a broader range of sectors.

[3] See Weitzman, M. 2010. What is the "Damages Function" for Global Warming – and What Difference Might it Make? *Climate Change Economics* 1(1): 57-69.

- **Improve valuation of non-market impacts.** Several participants emphasized the need to improve the valuation of non-market impacts and their representation in IAMs. This includes both improving the estimates of non-market impacts currently included in some models (e.g., health impacts) and incorporating non-market impacts currently missing from most models (e.g., ocean acidification, loss of cultural heritage, etc.).

- **Consider "outer measures" of climate damages.** A couple of participants highlighted the need for a highly simplified but inclusive "outer" measure of climate change damages that could provide an upper bound on the estimates. These participants suggested that current models are all "inner" measures that attempt to capture the individual subset components of the SCC to build up to the total SCC. Since it is very difficult to capture all of the individual components, these estimates tend to be low-end estimates.

Comments related to the communication of IAM results

Finally, many participants suggested potential future improvements related to the communication of the SCC and its use in decision making. These suggestions include the following:

- **Increase transparency.** Throughout the workshop, from Deputy Administrator Perciasepe and Under Secretary Koonin's opening remarks to Dr. Duke and Dr. McGartland's summary comments, transparency was a recurring theme. Numerous participants and speakers emphasized the need to increase the accessibility and transparency of the models, including their key assumptions, structural equations, calibrated parameter values, and the underlying empirical studies on which these values are based.

- **Communicate uncertainty.** The effective communication of uncertainty was another theme that pervaded the comments of participants. Given the significant uncertainty involved in the estimation of the SCC, numerous participants emphasized the crucial importance of fully and clearly communicating the uncertainty behind the estimates, including the relationship between uncertainty and time scale. Much discussion centered on how best to communicate model and parameter uncertainty so that decision makers and the public properly understand the uncertainty surrounding SCC estimates and the implications of this uncertainty. One specific suggestion along these lines was to emphasize that the precision in the final SCC estimates correlate with the precision that can be supported by the model inputs. For example, reporting the SCC with several significant figures gives a highly overconfident impression of the precision of these estimates.

- **Use a range of outputs.** Related to the communication of uncertainty, many participants encouraged increased communication and use of the full range of model outputs rather than focusing on one central value from a set of model runs. Opinions varied regarding the most effective way to communicate uncertain results, so more work in this area could be useful.

- **Consider other metrics.** Many participants questioned the usefulness and effectiveness of the SCC as a single criterion for regulatory analysis. Several participants discussed the potential shortcomings of cost-benefit analysis in a climate change context. Some participants indicated

that the SCC may be one relevant measure, but they encouraged the use of multiple criteria for regulatory analysis, in addition to the SCC. Participants suggested using additional measures to assess cost-effectiveness, such as using the shadow price of a range of policy targets as a reference.

- **Match model to objective.** Many participants underscored the importance of matching model type to analytical objective. Participants noted that a given question may be better addressed by one type of model than another. For example, a high-resolution model might be most appropriate for some analytical questions, such as assessing impacts to individual sectors, while a reduced-form model might be most appropriate for assessing other questions, such as the sensitivity of the outcomes to a wide variety of policy choices and model assumptions. Aggregated damage functions might address certain questions best while disaggregated representations of damages might best address others. Similarly, the time-scale of the analysis should appropriately match the analytical aims.

III. Chronological Presentation of Workshop Proceedings

This section presents the proceedings of the workshop in chronological order, including: workshop introduction; session presentations, question and answer sessions, and discussions; and closing remarks.

Workshop Introduction

The workshop commenced with a welcome and introduction by Elizabeth Kopits of the U.S. Environmental Protection Agency. She noted that this workshop was the first of two EPA- and DOE-sponsored workshops aimed at an open, scholarly dialog among top researchers about Integrated Assessment Models and climate change impacts and damage estimations. She explained that the impetus for the meeting arose from the recent interagency report on the SCC. She highlighted the need to update and revise the SCC; to incorporate new scientific findings as they emerge; and to improve transparency, availability, and understanding. She noted the need to spur efforts to fill research gaps, explaining that some would be difficult to fill while others would be more easily addressed by improvements in economics and science. Finally, she highlighted the need for increased collaboration between natural scientists and economists.

Opening Remarks

Following Dr. Kopits' introduction, Bob Perciasepe, U.S. Environmental Protection Agency Deputy Administrator, shared his opening remarks. Mr. Perciasepe began by thanking the participants for their work. He underscored the importance of the SCC in helping EPA to be a better decision maker, noting the important role that cost-benefit analysis (CBA) has played to drive EPA work throughout its 40-year history. He suggested that the SCC begins another chapter in EPA's history by creating a unifying measure and tool to use across different programs in the U.S. Government. Mr. Perciasepe also noted his healthy concern that CBA fails to capture many different issues. He highlighted the more ubiquitous and difficult aspects of the climate change question, with its numerous effects around the globe. He concluded that the SCC is an important common building block, but that it needs to be improved.

Mr. Perciasepe then raised a few key questions and challenges to the workshop participants. First, he asked if the current valuation methods adequately address all costs and catastrophic risks. He highlighted the possibility of irreversible impacts from climate change, noting the significant multigenerational effects from climate change. Mr. Perciasepe highlighted numerous impacts that remain unquantified in the reduced-form IAMs, including ocean acidification and loss of biodiversity. He questioned whether the breadth of impacts is captured by models, providing agricultural impacts from weather volatility as an example.

Next, Mr. Perciasepe asked whether there is a way to present the SCC transparently enough for the public to understand it. He noted that while the current estimate is an incomplete picture, many people see it as an all-encompassing portrait. He suggested perhaps listing the range of possible impacts and clarifying which are and are not reflected in current models. Finally, Mr. Perciasepe asked how best to account for the time horizons of impacts, given that emissions today may set the pattern for centuries. Mr. Perciasepe concluded his remarks by once again emphasizing that he values this work greatly, that progress so far has been remarkable, but that improvement is still needed and his challenges are intended to spur the iterative process forward.

Next, Dr. Steven E. Koonin, Under Secretary for Science at the U.S. Department of Energy, shared his thoughts from the perspective of DOE's chief scientist. He underscored the importance of the valuation endeavor, particularly to inform policy. He noted that the interagency report has already been used for multiple DOE Energy Conservation Standards, including the first U.S. government use of the report in the Energy Conservation Standard for small electric motors. He emphasized the importance of speaking the language of economics, to drive action on climate change. Acknowledging the complicated nature of the problem, he emphasized the importance of addressing it with rigor and transparency so that it is justifiable to non-experts. Finally, he noted that DOE has and will continue to sponsor integrated assessment work and climate modeling.

Second, Dr. Koonin presented his thoughts from the perspective of a scientist who has professionally done modeling work. He explained that the work so far has been good but a lot of progress still needs to be made. He noted that credible integrated assessment models differ in their results by an order of magnitude. Dr. Koonin explained his healthy skepticism about models, suggesting that all of the models are wrong, but some are useful. He asked for the models to be validated, for their differences and uncertainties to be outlined, and for improvements to be identified. He called for more data, and asked for metrics to validate model results. He then suggested that more elaborate IAMs are not necessarily more useful tools than simpler IAMs in every case.

Dr. Koonin concluded his remarks by describing a back-of-the-envelope approach to calculate the social cost of carbon. He began by noting that – given the long lifetime of carbon dioxide in the atmosphere – small, marginal changes in CO_2 emissions will have only minor impacts on the ultimate magnitude of climate change. Reducing emissions now can therefore be viewed as delaying the time in the future at which cumulative emissions targets are reached. He finished by suggesting that the notion of buying time is an interesting avenue to pursue for climate change valuation. If discounted to the present, the value of time bought might serve as a summary measure of marginal damages.

Progress Toward a Social Cost of Carbon

Dr. Michael Greenstone, who co-chaired the interagency SCC process when he served as chief economist for the White House Council of Economic Advisors, then presented an overview of the interagency process, including an example of how the SCC can be useful in a regulatory context. He started with the background and motivation for developing the SCC. He presented some of the impacts of climate change and an overview of U.S. climate change regulation. He noted the lack of climate change legislation and the early efforts to regulate greenhouse gases through the Clean Air Act. Given these emerging regulations, Dr. Greenstone presented the desire for a social cost of carbon to monetize benefits during regulatory impact analyses. He explained that the SCC is the monetized damage associated with an incremental increase in carbon emissions in a given year. He showed how it could be used to demonstrate net benefits from the otherwise costly emissions standards for light-duty vehicles.

Dr. Greenstone then summarized the key decisions and results from the interagency working group. He noted that the interagency process selected three commonly used IAMs to estimate the SCC: DICE, PAGE, and FUND. For socio-economic inputs and emissions trajectories, the interagency process relied on scenarios from the Stanford Energy Modeling Forum exercise EMF-22. The working group used four of the ten models and selected four business-as-usual (BAU) paths and one lower-than-BAU path that achieves stabilization at 550ppm in 2100. The interagency group parsed the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) to define the constraints of equilibrium climate sensitivity. They calibrated four distributions to the IPCC constraints and selected the Roe and Baker distribution. He noted that the interagency group decided to use a global measure of the SCC and decided against equity weighting. Dr. Greenstone explained that the interagency process uses three discount rates of 2.5, 3, and 5 percent.

The IAMs were run through 2300 to produce 45 separate distributions of the SCC for a given year. The distributions from each of the models and scenarios were averaged together for each year to produce three separate probability distributions for the SCC in a given year, one for each discount rate. The interagency group selected four SCC estimates for use in regulatory analyses. In 2010, these estimates are $5, $21, $35 and $65 (in 2007 US$). The first three estimates are the average SCC across models and emissions scenarios for the three distinct discount rates. The fourth value represents higher-than-expected impacts. The $21 estimate associated with a 3% discount rate is the central value.

Dr. Greenstone finished with a list of key areas identified for future research and advances in calculation of the SCC. This list included improvements related to: catastrophic impacts; translating physical impacts into economic damages; interactions between inter-sector and inter-regional impacts; adaptation and technological changes; incorporation of risk aversion; and valuing reductions of other GHGs.

During the question and answer session, one participant criticized the misleading presentation of four significant figures in the SCC estimates, which gives a highly overconfident impression of precision that is unfounded when the uncertainty ranges are so large. Another participant criticized the negligible impacts calculated by the models for 2°C of warming, highlighting the conclusion of the Copenhagen

Accord that this level of warming is dangerous. Dr. Greenstone explained that the process used the best available evidence on economic damages that were incorporated in IAMs at the time.

Session 1: Overview of Existing Integrated Assessment Models

Session 1 was moderated by Stephanie Waldhoff of the U.S. Environmental Protection Agency and included presentations by Jae Edmonds, Pacific Northwest National Laboratory; Stephen Newbold, U.S. Environmental Protection Agency; Christopher Hope, University of Cambridge; David Anthoff, University of California, Berkeley; Leon Clarke, Pacific Northwest National Laboratory; and John Reilly, Massachusetts Institute of Technology. The session provided an overview of existing integrated assessment models, including those used for the development of current U.S. government social cost of carbon values (DICE, PAGE, FUND), as well as other types integrated assessment models (GCAM, iESM, IGSM).

Overview of Integrated Assessment Models

Dr. Jae Edmonds presented an overview of integrated assessment models. He noted that IAMs integrate human and natural Earth system climate science and are useful for three reasons: to provide insights that would be otherwise unavailable from disciplinary research; to capture interactions between complex and highly non-linear systems; and to provide natural science researchers with information about human systems such as GHG emissions, land use, and land cover. He further noted that IAMs were never designed to model the very fine details, rather to provide strategic insights, for example about non-linear interactions.

Dr. Edmonds then mentioned the diversity of IAMs that are designed for multiple types of questions and problems, emphasizing the importance of choosing a model appropriate to the question or problem at hand. He then distinguished between the highly aggregated IAMs and the higher resolution IAMs. Highly aggregated models are often used to compare the costs and benefits of policy intervention. These models are typically composed of three components: emissions, natural Earth systems, and climate damages. Highly aggregated models often summarize information pulled from other, more detailed models or from off-line research in order to establish parameter values. The less aggregated, higher resolution models address a different set of questions associated with the details of the interactions between human and Earth systems. Higher resolution models are focused on cost-effectiveness rather than cost-benefit analysis, and are often used to identify the best way to accomplish a given objective.

DICE

Dr. Stephen Newbold presented a summary of Dr. William Nordhaus' DICE model, beginning with an overview of its historical development and applications. The DICE model, or Dynamic Integrated Climate-Economy model, includes an optimal economic growth model, a simplified climate change model, a damage function that represents the loss of economic output due to increased global surface temperatures, and the projection of abatement costs over time. The model solves for the optimal path of savings and abatement to maximize present value of discounted aggregate utility.

Dr. Newbold presented a brief overview of the model's structure, noting its Cobb-Douglas production function, "three-box" climate model calibrated to MAGGIC, and pure rate of time preference set at 1.5%. He noted that, contrary to how it was used in the interagency process, the social cost of carbon in DICE is typically calculated along an optimal path, where the SCC equals both the change in consumption in all future years from one additional unit of emissions in the current year, discounted to present value using the Ramsey consumption discount rate, as well as the tax on CO_2 emissions. The damage function in DICE was developed by choosing a functional form for aggregate climate change damages as a fraction of global economic output, and then calibrating the damage function parameters using a summary of empirical studies of climate change damages in all major categories, extrapolating among regions as necessary.

Dr. Newbold then briefly summarized several updates that have been made in the newest version of the regional counterpart of the DICE model, RICE2010. RICE2010 includes a few changes in parameters, as well as a revised set of region-specific damage estimates which are a function of temperature, sea level rise, and carbon dioxide concentrations. RICE2010 produces a near-term carbon price on an optimal path of approximately \$11/tonCO_2 as compared to approximately \$7.5 in DICE2007.

During the question and answer session, Dr. Newbold clarified the reasons for differences between DICE's \$7.5 SCC estimate and the estimates developed by the interagency group, noting the different population scenarios, GDP scenarios, discounting, and especially the probabilistic equilibrium climate sensitivity distribution used in the interagency process. One participant questioned the value in DICE for the relative risk aversion parameter, believing it to be many times too small. Dr. Newbold explained that the values were chosen to match observed market interest and savings rates. Another participant noted, based on his recent research, that if the relative risk aversion parameter is increased from 1.5 or 2, as in RICE and DICE, to 6, which is implied by some research on the "equity premium puzzle," then DICE produces very different estimates of the social cost of carbon.

PAGE

Dr. Christopher Hope presented a summary of his PAGE model, including its application to the SCC calculations. Dr. Hope focused on the PAGE09 model, which represents an update to the PAGE 2002 model used by the interagency working group. The PAGE09 model is written in Excel 2007 with an add-in module to perform Monte Carlo simulations. It considers methane (CH_4), nitrous oxide (N_2O), and high GWP gases in addition to carbon dioxide (CO_2). The model evaluates impacts for eight regions, in 10 particular analysis years through 2200, for different impact sectors and discontinuities. The model conducts 10,000 runs in Monte Carlo distributions to calculate probability distributions of outputs and is generally used to compare the benefits and costs of two policy options. Dr. Hope noted that while PAGE incorporates choices and costs of abatement and adaptation, they are not relevant to the interagency use of the PAGE model.

Dr. Hope then presented the new features of the PAGE09 version. This version of PAGE includes N_2O as a policy gas, includes sea level rise explicitly, models impacts as an explicit function of per capita GDP, constrains damages with a saturation line of 100% GDP, allows for the possibility of benefits for small temperature rise depending on input parameters, and measures impacts and costs as expected utility.

Dr. Hope enumerated several of the uncertainties treated by the PAGE model, including climate sensitivity response, CO_2 emission levels (which are only estimated by IPCC through 2100), global mean temperature rise, and global impacts, all of which influence the long right-tail of the impacts and social cost of carbon estimates. Dr. Hope demonstrated the major influences and sensitivities of the PAGE model, showing the model to be most sensitive to the transient climate response (TCR), where a change in the TCR of one standard deviation could increase the SCC by $60. Dr. Hope finished with a comparison of outputs from PAGE09 and PAGE2002 given the same set of inputs, showing that PAGE09 produces a mean SCC estimate of $100/ton$CO_2$ where PAGE2002 produced a mean estimate of $28. He noted that the increased impacts in PAGE09 can be attributed to the following characteristics of the new model: less effective adaptation, a higher chance of a discontinuity, better incorporating the possibility of very large impacts, and the use of 2005 dollars instead of 2000 dollars.

During the question and answer session, Dr. Hope explained that the extent of the time horizon and future assumptions are extremely important to the estimates produced by PAGE. For example, if the time horizon is extended to 2300, even when keeping emissions constant, the SCC estimate is increased by 20%. One participant raised the point that all of the IAMs incorporate the hidden assumption that damages are multiplicative which introduces an important bias. Finally, Dr. Hope clarified that the saturation line for damages of 100% GDP only becomes relevant in a very small number of model runs, under extreme parameters. He underscored the importance of looking at the full distribution of outputs rather than a single run when using the PAGE model.

FUND

Dr. David Anthoff then presented a summary of the FUND model, including a description of its basic structure. Of the three models used by the interagency working group, FUND is the most disaggregated, with 16 regions, multiple gases, and damage functions that are specified for numerous sectors. The model includes: a reduced form carbon cycle model for CO_2, CH_4, sulfur hexafluoride (SF_6), and sulfur dioxide (SO_2); a model to translate greenhouse gas concentrations into temperatures that incorporates a temperature lag; an ocean model to estimate sea level rise; a biodiversity model to estimate species loss; an impacts model with impacts based on temperature, sea level rise, species loss, and greenhouse gas concentrations; and feedbacks where the economic damages of climate change affect the economy growth rate. In FUND, exogenous variables include GDP, population, energy and carbon intensity, CO_2 emissions from land use change and deforestation, CH_4 emissions, and N_2Oemissions. Endogenous variables include CO_2 emissions, CO_2 emissions from natural feedbacks in the "dynamic biosphere", SF_6 emissions, and SO_2 emissions. All of the gas cycles and radiative forcing for each gas are modeled explicitly, while climate sensitivity is an uncertain distribution.

Dr. Anthoff then presented the impacts that are modeled in FUND, listing: the components of the health impacts model; the components of sea-level rise impacts as based on the analytical structure of Fankhauser (1994)[4]; and other impact categories, including agriculture, tropical storms, extra-tropical storms, forestry, heating energy, cooling energy, water resources, and species loss. For each impact

[4] Fankhauser, S. (1994). "Protection vs. Retreat - The Economic Costs of Sea Level Rise." Environment and Planning A **27**(2): 299-319.

sector, FUND includes a separate damage function that depends on the temperature predicted for that region and year. He noted that the sign of each impact could vary with geographic location and impact. The outputs of these damage functions are summed to aggregate impacts. Dr. Anthoff then presented the planned model modifications for FUND, which include: additions of impacts for ocean acidification, tourism, and river floods; an update to the energy consumption impacts; and a thorough evaluation of catastrophes.

Dr. Anthoff finished his presentation with a discussion of the interagency working group's use of FUND. He explained that he liked a lot of the working group's choices but pointed out three areas in which the models offer more than what was captured by the interagency process. He indicated that the working group estimates could be improved by incorporating: a fuller distribution of scenario uncertainty than the five EMF socio-economic scenarios; endogenous, non-constant discounting where the discount rate is related to the economic growth rate; and equity weighting to better capture the uneven distribution of climate change impacts.

During his presentation, Dr. Anthoff distinguished between two types of transparency in IAMs. He noted that in simpler models like DICE the simple damage function is itself easier to grasp, however the damage function's foundation and link to underlying studies is less clear. In contrast, in more complicated models like FUND, the damage functions themselves are more complicated, but their foundation and link to underlying studies is clearer.

During the question and answer session, one participant questioned the net benefits modeled by FUND for the first 3 degree Celsius temperature increase, attributing the benefits to agricultural sector benefits based on research from the early 1990s and health benefits from reduced cold weather deaths. Dr. Anthoff explained that FUND does not conduct primary impact studies, instead basing impacts on the existing literature. He further explained that climate damages produce differentiated impacts across the globe with poor countries most negatively affected. Without equity weighting, he explained, these damages do not significantly impact the aggregate. Finally, he noted that the social cost of carbon is related to marginal damages, not total damages, so it is the slope of the damages curve rather than the absolute value of damages that is important. Another participant agreed with the first participants' criticism of near-term net benefits, but noted that PAGE also produces some near-term benefits and there is the added consideration of weather variability. The same participant proposed that the low slope of the damage function indicates that FUND's bottom-up approach, while good, is missing some key aspects.

GCAM and Development of iESM

Next, Dr. Leon Clarke presented the climate impacts representation in GCAM, which is an example of one of the higher resolution IAMs described by Dr. Edmonds. Dr. Clarke explained that GCAM is a dynamic-recursive model that includes a climate model based on MAGICC and the energy-economy model developed by Dr. Edmonds and Dr. Reilly. While the model's basic inputs are similar to the more aggregate models, GCAM includes a much higher level of detail for each sector. For example, GCAM includes detail related to energy system resources, technology assumptions, demand technologies, and agricultural productivity. Dr. Clarke noted that GCAM is particularly useful for examining impacts that

involve interactions among the various systems represented in IAMs. However, he also noted that aggregating and monetizing all impacts is not a core objective of GCAM or similar, higher-resolutions IAMs.

Dr. Clarke included a list of priorities for incorporating impacts into PNNL/JGCRI's integrated assessment modeling. He outlined ways for pursuing these developments, including one dimensional integration (either all within GCAM or through linkages with other sector-specific models) and incorporating feedback with other systems by endogenizing interactions within the model or leaving them "hanging" off of GCAM. Dr. Clarke then presented three examples of areas where GCAM has been used to model impacts in a more detailed way, related to land use, energy, and water.

Dr. Clarke then provided two examples of linkages between platforms: the integrated Earth System Model (iESM) and the regional initiative. iESM is a research collaboration between the Pacific Northwest National Laboratory (PNNL), Oak Ridge National Laboratory (ORNL), and Lawrence Berkeley National Laboratory (LBNL). The effort has three primary tasks: to create a first generation integrated Earth System Model linking the human system components of GCAM to a physical Earth System Model (ESM), the Community Earth System Model (CESM); to further develop components and linkages within the iESM and apply the model to improve our understanding of the coupled physical, ecological, and human system; and to add realistic hydrology. Dr. Clarke noted that running GCAM without linkages to CESM takes approximately 20-30 minutes, but running GCAM with linkages and feedbacks can take as long as months. The regional initiative is an effort to integrate more detailed regional models into GCAM (e.g., the crop model EPIC or the whole building engineering model BEAMS).

During the question and answer session, one participant questioned the short-sighted, or "myopic", nature of recursive-dynamic models, particularly challenging the lack of oil price modeling. Dr. Clarke clarified that "recursive-dynamic" means that GCAM establishes market equilibrium at each time step before moving forward. He also noted that the oligopic nature of oil is not modeled in the IAMs.

IGSM

Dr. John Reilly concluded the presentation portion of Session 1 with an overview of the MIT Integrated Global System Model (IGSM). Dr. Reilly explained that the IGSM is a general equilibrium economic model with a full inter-sectoral structure. The model includes: impacts from numerous sectors including, agriculture, forestry, hydrology, trace gas fluxes, sea level change, land use change, and human health effects; a robust climate model with atmosphere, urban, ocean, and land components; and model outputs that include GDP growth, energy use, policy costs, global mean and latitudinal temperature and precipitation, sea level rise, sea-ice cover, and net primary productivity. The model includes numerous feedbacks and interactions between the economic model and the dynamic terrestrial ecosystems model. Dr. Reilly noted that the model includes and values the benefits and costs of adaptation, as well as both market and non-market (e.g., leisure) damages.

Dr. Reilly then discussed the characterization of uncertainty in the IGSM. Uncertainty in the model arises from: emissions uncertainties (due to uncertain socio-economic inputs); climate system response uncertainties; and greenhouse gas cycle uncertainties. Dr. Reilly discussed the impacts of different

stabilization targets, including the likelihood of different levels of temperature increase under each policy. He showed probability distribution functions for five different policy scenarios. He presented an uncertainty analysis that showed that the five cases used in the interagency process are conservative estimates of CO_2 concentration projections and do not capture the full range of IGSM estimates. Dr. Reilly also compared the IGSM scenarios to the IPCC SRES scenarios for global mean temperature change. Again, the IPCC results show a low bias and do not cover the full range of IGSM estimates. Dr. Reilly concluded that the higher impacts estimated by IGSM as compared to IPCC indicates that looking at the issues in an integrated way can produce different answers than looking at the issues individually.

Session 1 Discussion

Following Dr. Reilly's presentation, the discussion portion of Session 1 began. One participant noted the importance of IAMs as an essential tool. Acknowledging the difficulty of developing IAMs, he criticized the narrowness of the current IAMs, particularly regarding incorporation of damages. He noted the current IAMs' large emphasis on agriculture damages but highlighted the old and new literature that goes beyond agricultural damages. He noted that the damage levels currently modeled in the IAMs equate to the world reaching a given GDP level in 2103 instead of 2100, an insignificant change. The participant suggested that the IAMs should be broadened to incorporate effects such as changes in savings, investment, and growth rates, and perhaps even things like political stability.

Dr. Hope responded by noting that first, there is an advantage to not disaggregating sectors in that damage functions are more easily updated, and second, that integrated assessment modelers cannot claim to do the primary research, rather they incorporate other primary research and build in uncertainty. He noted that the only thing from the participant's discussion not included in PAGE is the political stability component, but he noted that if research quantifying political stability impacts existed, the model could incorporate it.

Another participant criticized the estimation of damages in terms of GDP, arguing it is not a good measure of human welfare. Dr. Reilly indicated that aspects of welfare are included and that a proper welfare analysis is done with consumption of different goods and their substitutability specified. Dr. Anthoff noted that the FUND damage functions are not quantified as a percent of GDP, but as a welfare loss equivalent to certain consumption loss.

Another participant asked whether there was any way to verify the models given that they are dealing with unprecedented conditions. Dr. Hope noted that verification is much more difficult for economic models than for Earth system models, and that more time, money, and research is needed to explore the issue. Dr. Reilly suggested focusing on mechanistic approaches. Another participant wondered whether the models could be verified through historical runs projecting forward to today. Dr. Reilly explained that there are so many degrees of freedom in the model, it is very easy to force the model to replicate historical events by adjusting input parameters.

Another participant discussed the vast uncertainty and guesswork involved in the IAMs and SCC estimates. He questioned how best to proceed given the unprecedented uncertainty around the SCC estimates. He proposed several options, including: forging ahead and producing a number; admitting

the uncertainty is too great and avoiding the exercise altogether; or some hybrid. He further questioned the applicability of cost-benefit analysis for climate policy decisions. Dr. Hope argued that despite the uncertainty, it is still beneficial to estimate the SCC. However, it is crucial to always present a range of values and an explanation of what is and is not included in the estimate, as well as an explanation of what information is needed to narrow the range.

Finally, a participant asked first how best to characterize various uncertainties that have not yet been extensively examined quantitatively in the literature (e.g., damages at higher temperatures, degree of reversibility of impacts and damages), and second, about the importance of feedbacks to growth and discount rates, noting that only one model incorporates such feedbacks. Dr. Newbold commented that feedbacks to growth and discount rates are very important if discounting is tied to consumption growth. Dr. Hope commented that negative discount rates might even be necessary if climate change welfare effects are significant enough, noting they are exploring the idea of negative discount rates in the latest version of PAGE. He also commented on the need for a high quality assessment of what the impacts would be of a much more extreme temperature increase than the typically analyzed 2 or 3 degree C increase. Finally, Dr. Anthoff commented that existing impact studies only examine a narrow range of temperature impacts, but that anything beyond these ranges must be extrapolated. He noted that eventually, assumptions must be made in order to extrapolate to more extreme temperatures, but that it would be best for the impact scientists to be involved in this exercise.

Session 2: Near-Term DOE and EPA Efforts

Session 2 was moderated by Ann Wolverton of the U.S. Environmental Protection Agency and included presentations by Robert Kopp, an American Association for the Advancement of Science (AAAS) Science & Technology Policy Fellow hosted by U.S. Department of Energy; Nisha Krishnan, Resources for the Future/ICF International; and Alex Marten, U.S. Environmental Protection Agency. The session provided an overview of near-term DOE and EPA Efforts, including the DOE proposed impacts knowledge platform and the EPA generalized modeling framework.

Proposed Impacts Knowledge Platform

Dr. Bob Kopp began the presentations by introducing the possibility of an impacts knowledge platform. This platform would constitute an effort to help overcome the barrier between natural scientists and economists, to help economists understand and use the best available natural science. Developers of the platform are working to identify which data should be included and what is needed to inform local and regional policy making.

Ms. Nisha Krishnan then presented the Global Adaptation Atlas, an existing adaptation planning and research initiative that DOE partially funded to help inform the consideration of an impacts knowledge platform. Ms. Krishnan explained that the Adaptation Atlas, which is intended to inform policy making, is currently in beta form, online, and available (at http://www.adaptationatlas.org/). The Atlas currently contains twenty studies from the peer reviewed literature on different human impacts of climate change. The Atlas is a web-based application that enables user-driven, dynamically-generated maps of climate impacts and adaptation activities, where the user is able to select a location, timeframe, and scenario and view a map corresponding to their decision filters.

Ms. Krishnan explained that the Atlas was assembled by soliciting data and study results from approximately 300 studies, which returned only 20-30 responses. She noted that researchers seemed hesitant to share data, even from peer-reviewed studies. Solicitations focused on five sectors: food, water, land, health, and livelihood. The data was then translated into a visual, spatial format; every layer was tagged with IPCC scenarios, timeframes, and locations; and 'meta' filters were applied to harmonize across time, theme, and assumptions so that the layers could be combined in a simplistic overlay. Ms. Krishnan explained that the Atlas also attempted to investigate uncertainty, but received only one response from their solicitations. The Atlas only incorporates sensitivity analysis, which should be incorporated into the online tool by the end of 2011.

Proposed Generalized Modeling Framework

Dr. Alex Marten then described a preliminary scoping study by EPA to develop a generalized modeling framework. Dr. Marten explained that the idea arose from the interagency SCC process, and is intended to explore ways to provide a more transparent and standardized modeling framework that could more easily incorporate existing and future research on climate science and economic damages. Ideally, such an approach would also allow for a better understanding of the sources of differences in SCC estimates and the drivers of model results. Dr. Marten also emphasized the importance of providing detailed up-to-date documentation and of designing the model code to be open source and freely available to the public.

Dr. Marten identified the following key characteristics for a more generalized modeling framework: general and flexible enough to incorporate new research and to nest other commonly used IAMs; fully transparent; probabilistic; and modular to allow replacement of components over time. Dr. Marten then provided a brief overview of a prototype for such a framework, highlighting its similarities to other commonly used IAMs; its current use of MAGICC, a relatively robust climate model compared to some reduced form models currently being used in IAMs; its potential to represent natural capital; and its potential to include climate-population feedbacks and endogenous emissions. Dr. Marten explained that such a framework may be designed to carefully distinguish between several different types of climate change damages (e.g., market based with sectoral breakdowns, direct capital destruction, consumption equivalent health damage, etc.) for transparency and accuracy. Dr. Marten emphasized the concept of creating a general framework as a way to better facilitate incorporation of new research on climate change-induced damages, as the research becomes available.

Dr. Marten noted that the framework is in an early prototype stage. The basic architecture of the framework is being tested by using specific parameter settings intended to closely approximate versions of DICE, PAGE, and FUND as used by the interagency workgroup. Dr. Marten then identified further steps that would be required for the framework to become fully functional, including: expanding and modifying the model structure based on feedback from the workshop participants and other informal reviewers, incorporating currently available and new studies on climate change damages as they are published, external peer review, and eventual public release.

Session 2 Discussion

During the discussion section, one participant commended the idea of a generalized modeling framework noting it should be feasible. He also underscored the importance of openness, and criticized the lack of EPA and DOE policy requiring the projects they fund to be open source. He suggested that opening up the process would encourage interest in the topic and reduce barriers to entry into the field. Dr. Kopp responded that DOE has been supporting some efforts to make the process more open.

Another participant noted that the components of the generalized modeling framework are very similar to FUND, suggesting EPA draw on the capabilities of FUND in developing this framework and noting that the challenges are programming questions not scientific questions. Another participant noted the community integrated assessment model in Europe that is looking at non-linear changes and stochastic models, suggesting it might also be helpful to build on.

Another participant suggested moving away from matching or incorporating existing models as the existing models need significant improvement and use old research. He highlighted the almost unanimous comments from the workshop participants indicating a significantly new approach is needed. Dr. Marten explained that the standardized models are intended to facilitate comparison of existing models and incorporation of new science. Dr. Wolverton noted the need to change the structure of the models as well as the underlying science.

Another participant questioned the use of IAMs generally and wondered if it might be worth talking to OMB about alternative tools. Dr. Wolverton underscored the involvement of OMB in the 2009-2010 full interagency process, as well as the inclusion of the workshop discussion in future interagency discussions of the SCC.

One participant highlighted the simplicity of the IAMs, particularly as compared with climate models. She contrasted FUND, a model built by two people, with climate models that have large teams and $5 million per year for updates and maintenance. She suggested two options moving forward. One option would be to continue developing what she called “toy models” to transparently run assumptions. Another option would be to highlight the importance of the exercise and outline exactly what would be required to develop the models properly.

Finally, a last participant emphasized the need for more basic impacts studies before working to improve the models themselves.

Session 3: Critical Modeling Issues in Assessment and Valuation of Climate Change Impacts

Session 3, Part 1

Session 3 was split into two parts occurring in the afternoon of Day 1 and the morning of Day 2. The first part of Session 3 was moderated by Ann Wolverton of the U.S. Environmental Protection Agency and included two presentations by Ian Sue Wing, Boston University, one as a replacement for Karen Fisher-Vanden, Pennsylvania State University, as well as a presentation by Brian O’Neill, National Center for Atmospheric Research. The session began to explore critical modeling issues in assessment and

valuation of climate change impacts, including: sectoral and regional disaggregation and interactions, adaptation and technological change, and multi-century scenario development and socio-economic uncertainty.

Sectoral and Regional Disaggregation and Interactions

Dr. Ian Sue Wing started the Session 3 presentations with a discussion of the sectoral and regional representation of economic damages in integrated assessment models. Dr. Sue Wing presented the basic structure of IAMs as a three model structure including an economic model, climate model, and impact model. He then presented the set of nine disaggregated region- and sector-specific equations that would be used to construct an IAM in the absence of resource limitations. He noted that researchers are most knowledgeable about the economic model components, with 40 years of experience; relatively knowledgeable about the climate components, with 20-25 years of experience; and least knowledgeable about the impact model, which is relatively new and the centerpiece of the workshop's discussion.

Dr. Sue Wing then walked through the nine equations, noting which components comprised each equation. He highlighted the increasing uncertainty and unknowns as he progressed from the economic model to the climate model and then to the impact model. He noted the need to separate damages and costs, creating two separate response surfaces that are multiplicative.

Dr. Sue Wing noted that in the absence of resource limitations, IAMs would be constructed with sectoral and regional detail in production, consumption, and climate damages. He explained that impacts would first be elaborated by category of physical endpoint, sector, region, and future time period, based on simulated climatic changes at the regional scale. Only then would the models aggregate across endpoints to generate sector-by-region trajectories of shocks. Instead of aggregate damage functions, the models would incorporate a transparent causal chain from both ex ante shocks and ex-post adjustments in regional/sectoral output and consumption to ultimate welfare effects.

Dr. Sue Wing noted that in current models, particularly DICE, the complexity and dimensionality of the issue has been boiled down and combined, with the models dependent only on temperature. Dr. Sue Wing then enumerated the many difficulties in attempting to build his idea of an ideal model, emphasizing the lack of empirical or detailed modeling studies, particularly studies that go beyond 2050. He noted the inherent difficulty in maintaining detailed estimates given increasing uncertainty as projections extend further forward in time. Dr. Sue Wing identified computable general equilibrium (CGE) models as a promising new direction, particularly given their increasing skill at regional scales and their explicitly multi-regional/multi-sectoral approach. However, he also noted their problematic recursive-dynamic (and therefore myopic) nature and limited time horizon.

During the question and answer session, one participant challenged the notion that intertemporal valuation is done well and asked how ecosystem services are represented. Dr. Sue Wing suggested ecosystem services be valued using a Ramsey framework specified with ecosystem service constraints. The participant commended the answer on how to incorporate ecosystem services but noted there is generally little knowledge about the welfare derived from non-monetized services, such as ecosystem

services in a climate change context. Dr. Sue Wing acknowledged the current lack of knowledge but indicated there are ways to make progress. Another participant asked about climate impacts damages and the regional and local specificity from the perspective of infrastructure risk. Dr. Sue Wing explained that climate damages can be set to change capital accumulation by reducing investment rates or directly destroying capital stocks. However, he noted the difficulty associated with projecting specificity into the future.

Adaptation and Technological Change

Dr. Ian Sue Wing then presented the effects of adaptation and technical change on the SCC, on behalf of Dr. Karen Fisher-Vanden, who was unable to attend the workshop due to illness. He noted numerous challenges to incorporating adaptation: the inherent difficulty in modeling adaptation, requiring advancements in modeling techniques; the limited coverage of empirical work on adaptation and additional difficulty of incorporating the studies into IAMs; and the lack of adaptation-related technological change in current IAMs. He emphasized the critical need for empirical studies, as well as research focused on bringing the results from state-of-the-art empirical studies into modeling frameworks.

Dr. Sue Wing then walked through the important model features needed to represent adaptation, given the unique characteristics of the adaptation process. In order to incorporate adaptation, models need to include: explicit modeling of climate damages and impacts so that reactive expenditures and proactive investment can be estimated; inter-temporal decision making under uncertainty; endogenous adaptation-related technological change, as distinguished from mitigation-related technological change, (which differs in the nature of inducement and the public versus private nature); regional and sectoral detail since adaptation occurs on local and regional scales; and a connection with empirical work on impacts and adaptation.

Dr. Sue Wing then examined existing IAMs, noting the four models that deal with adaptation: AD-WITCH, AD-DICE/AD-RICE, PAGE, and FUND. He noted that only three of the four models are inter-temporal and only one (AD-WITCH) has proactive adaptation. Dr. Sue Wing then identified the three main existing empirical summary studies on adaptation and recommended four areas for future research: decision making under uncertainty; adaptation-related technological change; empirical work on adaptive capacity; and dynamics of recovery.

During the question and answer session, one participant encouraged the modelers to consider and incorporate suffering in addition to mitigation and adaptation. Dr. Sue Wing acknowledged that suffering was missing from the models in their current state using aggregate output good. He suggested that suffering be incorporated using the regionally and sectorally disaggregated approach, but noted the difficulty with monetizing effects on culture. Another participant commented on the difficulty in separating adaptation from other capacity-building exercises, particularly in developing countries. He also commented on the purely theoretical progress in incorporating adaptation, again calling for more empirical studies.

Multi-century Scenario Development and Socio-Economic Uncertainty

Dr. Brian O'Neill delivered the last presentation of the day, on multi-century scenario development and socio-economic uncertainty. He emphasized the vast uncertainty and the importance of years beyond 2100 in SCC estimates. He then presented the assumptions made by the interagency SCC process, along with alternate estimates that could have been assumed. He explained that the interagency process used five EMF-22 scenarios, which they extended to 2300 using simple methods. Dr. O'Neill presented a series of graphs that independently plotted the interagency projections for global population, GDP, and carbon dioxide emissions along with alternate projections. These graphs demonstrated the narrow range of uncertainty captured by the interagency process – which sought to capture a wide range of emission estimates, combined with reasonable and internally consistent assumptions for the other two factors - compared to estimates of each factor when analyzed independently.

Dr. O'Neill showed that the global population estimates to 2100 used by the interagency process captured significantly less uncertainty than the estimates produced by the IPCC Fourth Assessment Report (AR4), the United Nations (UN), and the International Institute for Applied Systems Analysis (IIASA). Dr. O'Neill then demonstrated that the interagency estimates capture an even smaller portion of the range of UN and IIASA estimates when examining global population to 2300. He noted that the UN long-run estimate that aligns with the interagency estimates is not the most likely scenario, rather a mathematical benchmark to produce roughly stable population size.

Dr. O'Neill then presented a similar story regarding global GDP. He showed that as compared to the IPCC AR4 estimates, the interagency process captured a small portion of the range of possible estimates for GDP to 2100. Compared to a study projecting GDP to 2300, the interagency process only captured a tiny fraction of the range of estimates – the uncertainty in the study was orders of magnitude larger than the uncertainty in the interagency process.

Dr. O'Neill finished by showing the interagency scenarios did a better job of capturing the range of estimates for carbon dioxide emissions through 2100. The interagency estimates for emissions through 2300 covered a higher and wider range than the Representative Concentration Pathways (RCPs). Dr. O'Neill concluded that the interagency process captured an overly narrow range of uncertainty in population and GDP over the entire time horizon, especially in the long term, but was reasonably consistent with the range of emissions in the literature.

Dr. O'Neill listed many issues with multi-century scenario development, noting the fact that uncertainty ranges in the literature might themselves be too conservative given the vast unknowns of predicting 300 years into the future. He recommended demonstrating the key sources of uncertainty, using full uncertainty instead of a range of best estimates, considering a substantially wider range of socio-economic futures through 2100 and 2300, considering simpler approaches to damages in the very long term, improving how uncertainty in results is characterized, and considering linking to the evolving work on RCPs and socio-economic scenarios consistent with them.

Session 3, Part 1 Discussion

Following Dr.O'Neill's presentation, the discussion portion of Session 3, Part 1 began. One participant noted that adaptation should depend on the rate of temperature change, not just temperature. Another participant defended the models, noting that FUND impacts do depend on the rate of change in some sectors and that non-market impacts, such as health impacts, are incorporated in models such as PAGE and FUND. Dr. Sue Wing clarified the distinction between quantifiable non-market impacts and non-quantifiable non-market impacts such as cultural loss.

Another participant questioned the seeming lack of constraints in the population predictions presented by Dr. O'Neill. Dr. O'Neill attributed the vast population increases to technological change, explaining that it was probably hard to imagine 8 billion people on the planet when there were only 500,000.

In response to another question, Dr. Sue Wing recommended representing the elasticity of substitution dynamically, to capture adaptive capacity.

Another participant questioned the relationship between population and GDP, particularly the possibility of a low population, high GDP world. Dr. O'Neill clarified that there is no widely accepted theory between population growth and GDP. The same participant recommended caution in linking the SCC exercise to RCPs, as the assumptions may differ. He then underscored the importance of ensuring that assumptions about economic growth are consistent with or feed into the assumptions about discounting in a Ramsey framework. A different participant noted the need to examine vulnerable populations within developed countries. Dr. Sue Wing indicated that in addition to more regional impacts work, there is a need for quantitative historians to quantify damages from historic impacts.

One participant commented that the criticisms of IAMs are great for the modelers to hear, even if not all are well-deserved. He noted that the importance of scenarios after 2100 also depends on the lifetime of gases. And finally, he explained that the modelers' choice to narrow uncertainty in population and GDP was likely a choice to develop reasonable estimates out of profound uncertainty. Dr. O'Neill responded that clearly communicating uncertainty was critical. The ensuing discussion concluded that even though projecting through 2300 is very difficult, it is nonetheless important if conditions after 2100 have a significant effect on results. One participant suggested the only option was to use theoretical, likely Bayesian techniques to do so. Dr. O'Neill added that the marginal nature of SCC estimation constrains the conversation, noting the models can be used for other purposes.

One participant noted that a sense of urgency needs to enter the conversation given the small window of time left to act to address climate change and the importance of these estimates in potentially influencing the stringency of U.S. regulations. Instead of continuing with incremental adjustments to SCC estimates, she argued for the addition of normative economics to value things like culture. A final participant noted that if we continue to emit significant amounts of carbon dioxide, our climate future is known. He cautioned that even proactive adaptation may not work.

Session 3, Part 2

Session 3 resumed on Day 2 after brief opening comments from Elizabeth Kopits, U.S. Environmental Protection Agency. The second part of Session 3 was moderated by Robert Kopp on behalf of the U.S.

Department of Energy and included presentations by Gerard Roe, University of Washington; Martin Weitzman, Harvard University; Timothy Lenton, Unversity of East Anglia; Michael Toman, World Bank; and Michael Hanemann, University of California, Berkeley. The session continued to explore critical modeling issues in assessment and valuation of climate change impacts, including incorporation of climate system uncertainty, extrapolation of damage estimates to high temperatures, Earth system tipping points, potential economic catastrophes, and nonmarket impacts.

Incorporation of Climate System Uncertainty into IAMs

Dr. Gerard Roe presented an overview of what we do and do not know about climate projections. He started by stating that given the complexity of the weather and climate systems, any knowledge and skill regarding climate change is remarkable. Dr. Roe underscored the fact that uncertainty does not imply ignorance. Dr. Roe then discussed the concept of climate sensitivity, "the long-term change in annual-mean, global-mean, near-surface air temperature to a doubling of CO_2 above preindustrial values", which is used as the benchmark to compare different estimates. Dr. Roe presented several different estimates of climate sensitivity, showing the long right tail of estimates.

Dr. Roe then demonstrated that climate sensitivity is uncertain because the magnitude of past forcing, particularly the forcing of aerosols, is uncertain. Through a series of graphs, he showed that all of the variables in the global energy budget equation, (global mean temperature change, greenhouse gas warming, and ocean heat storage) are well-observed and well-constrained, except for the cooling effect from aerosols. This uncertain cooling effect leads to uncertainty in total climate forcing. Dr. Roe then showed that dividing the well-constrained temperature change by the poorly-constrained climate forcing results in the fat-tail of climate sensitivity. Dr. Roe further demonstrated the source of climate sensitivity uncertainty through use of classic feedback analysis models. Dr. Roe noted that the prospects for narrowing climate sensitivity uncertainty are limited.

Dr. Roe then presented projections of the climate commitment, if all anthropogenic emissions were to cease immediately. He explained that uncertainty in the climate response to current concentrations arise from the uncertainty in climate (aerosol) forcing. If radiative forcing has been high, climate sensitivity is low, and the temperature response could be lower than expected. However, if radiative forcing has been low, climate sensitivity is high, and the temperature response could be higher than expected. Dr. Roe concluded that uncertainty in climate sensitivity and climate forcing are not independent.

Next, Dr. Roe presented the transient evolution of climate impacts, showing that if climate sensitivity is high, it will take the climate a long time to adjust. This is due to the diffusive nature of ocean heat uptake and the slow, extended growth of the fat tail. Dr. Roe then explained that fixed carbon dioxide stabilization targets are an inefficient way to achieve a climate goal. Instead, policies should be implemented, observed, and then adjusted appropriately. He suggested that a flexible emissions strategy that adjusts over time could significantly reduce risk and uncertainty, and may be more cost-effective than rigid policies. Finally, Dr. Roe showed that global climate averages are not strong predictors of local climate change.

During the question and answer session, one participant underlined the significant unknowns under a high sensitivity trajectory and the need to fully flesh out the flexible emissions strategy suggested by Dr. Roe. The value of policy flexibility depends crucially on the feasibility of learning more about key uncertain parameters in a reasonable span of time. Another participant raised the issue of bio-geo-chemical feedbacks and their effect on results. A third participant pointed out that the policies under a flexible emissions strategy would look the same as current policies at the present time.

A final participant suggested that given the uncertainty caused by aerosols, the best way to gather information and knowledge about climate would be to simply turn off aerosol emissions. Dr. Roe agreed, noting that a decade would be needed to see the full effects. Dr. Kopp noted a recent paper in *Nature Geoscience* on the learning that could occur by turning off aerosols.

Extrapolation of Damage Estimates to High Temperatures: Damage Function Shapes

Dr. Martin Weitzman then presented the issue of damage function shapes, particularly when examining extreme temperature increases. Dr. Weitzman started by presenting the complicated and challenging nature of the valuation exercise. He described a long chain of tenuous inferences and deep, fundamental uncertainties on which impacts valuation relies. Acknowledging that the current models are reasonable in their assumptions, he explained that very different results can be produced with a different set of reasonable assumptions. He noted, in particular, the sensitivity of the estimates to how the tails are modeled and incorporated.

Dr. Weitzman continued by challenging the basic functional form of the damage functions. He argued that the greatest need to improve the IAMs is not for empirical studies, rather for a reevaluation of the fundamental structure of the models and damage functions. He questioned the approach of using quadratic damage functions, criticizing their low reactivity by highlighting an example where a 12 degree temperature increase only reduces output by 26 percent. He noted the high degree of substitutability between consumption and avoided impacts in current models, suggesting that an elasticity of substitution lower than one would greatly influence model results.

Dr. Weitzman then made a series of suggestions. He suggested that it is important to investigate the influence of extreme events, noting that model results depend non-robustly on seemingly obscure assumptions such as tail size, functional forms, parameters, and the pure rate of time preference. Dr. Weitzman suggested that the uncertainty with using cost-benefit analysis to estimate the SCC be communicated clearly and openly. He suggested that, despite the large inability to estimate extreme tail behavior and welfare disasters, it would still be beneficial to invest in research in these areas. He suggested that the fat tail risks of proposed solutions (e.g., nuclear power, carbon capture and sequestration) be considered alongside the fat tail risks of climate change. He suggested that the worst-case scenarios in the fat tails of climate impacts provide reason to develop emergency backstop geoengineering solutions. Finally, Dr. Weitzman concluded by suggesting we hope for the best and prepare for the worst.

During the question and answer session, one participant seconded the call for backstop research that will help to promote the ability to undertake mid-course corrections. Dr. Weitzman supported this,

arguing that climate change has the probability of being the worst fat-tailed issue. Another participant noted that even if the climate trajectory follows the mid to low IPCC projections, the consequences could be disastrous. He argued that geoengineering is the biggest fat tail problem, with the possibility of disaster outcomes. He suggested focusing the discussion more on known problems and less on speculative issues. A third participant noted the huge potential health effects of geoengineering solutions.

Earth System Tipping Points

Next, Dr. Tim Lenton discussed the issue of Earth system tipping points, which he explained are not necessarily high impact, low probability events, but may be high impact, high probability events. Dr. Lenton began with a definition of tipping elements and tipping points; where a tipping element is a component of the Earth system, at least sub-continental in scale (~1000km), that can be switched, under certain circumstances, into a qualitatively different state by a small perturbation; and a tipping point is the corresponding critical point at which the future state of the system is qualitatively altered. He then presented historical examples of abrupt climate changes, including bifurcations, noting that the Holocene has been unusually stable so far. Dr. Lenton then explained that policy-relevant tipping elements are those where: human decisions this century determine whether the tipping point is reached; the change will be observed this millennium; and a significant number of people care about the system.

Dr. Lenton then provided several examples of policy-relevant tipping points, including their estimated proximity in time, or probability of occurrence with increasing levels of global warming above the present temperature. Dr. Lenton explained that the probability of tipping points being reached under three different warming scenarios was established using imprecise probability statements elicited from experts. Experts were asked what the probability of reaching a given tipping point was under the three different scenarios. Dr. Lenton then presented several examples of tipping elements with the corresponding likelihood of occurrence based on expert elicitation. His examples of tipping elements included the Greenland ice sheet, the West Antarctic ice sheet, the Amazon rainforest, and El Niño/Southern Oscillation. He noted that it is important to assess rate and reversibility, as well as proximity, when identifying the most policy relevant tipping points. For example, the expert elicitation indicates that melting of the Greenland ice sheet, melting of arctic summer sea ice, and Amazon dieback are some of the more near-term thresholds that we face. However, the consequences of crossing a tipping point are not generally felt immediately when a tipping point is crossed. For example, although the Greenland ice sheet might be set on an irreversible path to near-complete destruction, the completion of the process would likely take several centuries. The length of this timescale, across which the effects of a tipping point are felt, is a key trait affecting policy relevance.

Dr. Lenton then indicated that according to the expert elicitation, there is a 16 percent probability that one of five tipping points will be passed under 2-4°C warming and a 56 percent probability that one of five tipping points will be passed under 4°C warming. He explained that there may also be interactions between tipping points including both positive and negative feedbacks. For example, a weakening of the Atlantic thermohaline circulation could end up disrupting the seasonal onset of the West African Monsoon, which in one model could lead to a greening of the region, a rare positive impact. The

strengthening of the Indian summer monsoon is a possible tipping point that is perhaps more sensitive to aerosols than to temperature changes. GHG impacts on this tipping element are likely being offset by the already occurring brown haze in the region. Finally, Dr. Lenton included several prospects for early warning signals, which could help societies manage the risk posed by tipping points. These include slowing down of a climate system (e.g., lower frequency of oscillation), increasing variability, and skewness of response.

During the question and answer session, one participant suggested that the dieback of ocean phytoplankton might be a candidate as a tipping element. Another participant questioned the classification of changes as tipping points, distinguishing elements that involve tipping physics from elements that are simply subject to large changes. Dr. Lenton agreed with the distinction. As an example, he noted summer ice melt involves fluctuation, not bifurcation; but winter- or year-round- ice melt is actually a switch to an alternate state. Dr. Lenton further noted that this distinction may not matter for policy purposes. Another participant suggested abrupt change occurs where strong spatial gradients exist. Dr. Lenton agreed that effective tipping points exist where the underlying climate driver is smooth.

A different participant posed the layman's question of how to distinguish between natural phenomenon and man-made events. Dr. Lenton responded that tipping points are affected by a combination of natural variability and gradual anthropogenic variables. He noted, however, that tipping points are matters of concern regardless of their drivers. Another participant initiated a discussion about the economic basis of the precautionary principle. Dr. Weitzman suggested non-linearity in utility was a more useful concept, pointing out people's natural risk-averse nature.

A final participant noted that two of the three highly aggregated models do incorporate tipping points. He suggested the need for primary economic studies to quantify impacts. Dr. Lenton acknowledged the effort made in the models, suggesting room for improvement. He specifically cited a need for multi-variate forcing, disaggregation, and better impact quantification. He suggested studies on society's response to other types of historical shocks.

Potential Economic Catastrophes

Dr. Michael Toman then presented his thoughts on the social cost of carbon and risks of climate change catastrophes. Dr. Toman started by commending Dr. Lenton's presentation, particularly its emphasis that tipping points may be closer in time and more serious than originally anticipated. Dr. Toman then outlined the two types of global climate catastrophes: "unfolding" catastrophes and "cascading" catastrophes. He explained "unfolding" catastrophes are those Dr. Lenton discussed. "Cascading" catastrophes are the much less studied global catastrophes that arise from the cumulative effect of a sequence of more localized climate change-induced harms reinforcing each other. Dr. Toman highlighted the very limited literature on quantitative global catastrophe valuation.

Dr. Toman then presented the standard rational choice approaches and the challenges with applying them to value global climate catastrophes. He noted the limited information on possible states of the world, the fat tails of the distribution, and, particularly, the indication from behavioral economics of

systematic assessment errors by the general public. He argued that decision makers need to exercise their judgment as agents of the general public in evaluations.

Dr. Toman then presented three possible response options: drastic global greenhouse gas reduction; massive anticipatory adaptation; and particulate injection into the upper atmosphere. He evaluated each option on four evaluation criteria: effectiveness in mitigating risk; cost of implementation; robustness to be effective even with surprises in evolution of climate change threats; and flexibility to modify response as information about risks changes. He finished with a matrix comparing the three options.

Dr. Toman finished his presentation by explaining that there still exists a large role for standard cost-benefit analysis in estimating the social cost of carbon. He noted that CBA does not do a good job of incorporating the fat tails, but noted that was not reason enough to abandon it entirely. He then presented three approach options for strengthening response options for catastrophe mitigation: the safe-corridors approach, soliciting expert judgments on alternatives, and soliciting public feedback on alternatives.

During the question and answer session, several participants questioned aspects of Dr. Toman's matrix of possible response options. Dr. Toman clarified that the matrix was intended to provide illustrative examples, rather than present a normative study on policy options. He agreed with two participants' emphasis on the importance of portfolio approaches and sequence of policy options. He also clarified several criticisms of the matrix's cost evaluation of different policy options. Finally, in response to another question, Dr. Toman explained this approach should not be downscaled to individual policies or categories of within-country investments.

Nonmarket Impacts

Dr. Michael Hanemann concluded the presentation portion of Session 3 with his presentation on nonmarket impacts. Dr. Hanemann gave his presentation remotely, by phone. He emphasized four points in his presentation: spatial and temporal aggregation understates impacts; extreme local events account for most of non-catastrophic damages; risk aversion should be accounted for; and impacts are multi-attribute and understated by a univariate utility function that treats consumption as a perfect substitute for environment. Dr. Hanemann showed that non-market impacts from climate catastrophe, even when underestimated make up the majority of the damages estimated by DICE.

Dr. Hanemann presented impact studies done in California using spatial downscaling. He argued that increased transparency results from spatial and temporal disaggregation. He noted that impacts and adaption are spatially and temporally heterogeneous. Any aggregation or averaging of these impacts results in underestimation of damages. Dr. Hanemann noted the asymmetrical distribution of positive and negative damages, with greater negative damages. He highlighted that this distribution is often represented symmetrically in IAMs. Dr. Hanemann also noted the relative importance of increasing frequency of extreme events as compared to increases in temperature.

Dr. Hanemann concluded that there is a great need to downscale and disaggregate models. He suggested a modular approach incorporating a network of models. He argued that damage functions

are too simple in current models. Dr. Hanemann suggested that climate change impacts be reframed in terms of risk, with greater emphasis on downside risk-adjusted impact. He also noted the need to treat consumption as an imperfect substitute for the environment.

Session 3, Part 2 Discussion

Following Dr. Hanemann's presentation, the discussion portion of Session 3, Part 2 began. During the discussion session, several participants questioned the ability to downscale data for the entire globe. Several participants suggested that the data is not good enough globally to support this level of spatial and temporal disaggregation. They noted that California and the southwest U.S. have particularly good data and a particularly strong climate signal. One participant wondered whether a bottom up, national model could help produce a factor that could be used to adjust estimates from existing global aggregate models. Dr. Hanemann responded that it is still beneficial to disaggregate in addition to working with global models. He noted that there is a need for several different types of models that can speak to each other. He highlighted the value of disaggregated information for transparency and communication. He argued that the level of downscaling might be different for different parts of the world. For example, he suggested doing a complicated disaggregated sectoral analysis for 3-5 regions, extrapolating to the U.S., and then conducting a more simple analysis for the rest of the world.

Several participants argued for the need for aggregated models. One participant highlighted the short time scales and lack of proper climate signal in most regional modeling. Dr. Roe used the example of river erosion modeling to suggest the need for aggregate functions to encapsulate the principles of very complicated phenomenon. Another participant cautioned about the indeterminacy of downscaling. One participant suggested that given the important role of aggregated, simple, reduced-form models, it is important to reevaluate and refine the form of current damage functions in IAMs. A final participant suggested the need to rethink and reframe the current aggregate models (e.g., by adjusting the damage functions) to better qualitatively describe impacts, rather than attempting to introduce a lot of additional components and details through disaggregation.

Ultimately, several participants argued for a two-pronged approach to modeling: disaggregated, detailed local modeling and aggregated modeling. One participant noted that the European Commission is conducting high resolution studies in Europe, which is complementary to highly aggregated studies.

During the discussion, several participants again highlighted the need for better empirical studies on physical impacts and monetization. One participant highlighted that regional calibration is already incorporated into current modeling, but that more studies are needed to improve that calibration. Another participant suggested the incorporation of contingent valuation, choice elicitation, and other methods of non-use valuation.

Another topic discussed during this session was the role of the SCC and other valuation methods. One participant distinguished between the need to outline a research agenda to characterize and monetize impacts and the need to improve the necessarily crude and narrow exercise to develop an SCC number for OMB guidance. Another participant emphasized the need to articulate regional impacts and to engage the public, regardless of whether regional impacts are summed to a single number. A third

participant suggested that the economic impacts work, and specifically the SCC, be updated to reflect the urgency and seriousness of climate change described by natural scientists. Lastly, a participant underscored the regulatory importance of the SCC as the communication message to the world. As such, she suggested two short-term improvements to the SCC: to tie down the high end of damages and to make the discount rate endogenous to growth. Another participant noted this is not as straightforward as the commenter makes it sound.

Session 4: Implications for Climate Policy Analysis and Design

Session 4 was moderated by Charles Griffiths of the U.S. Environmental Protection Agency and included presentations by Raymond Kopp, Resources for the Future; Geoff Heal, Columbia University; Nathaniel Keohane, Environmental Defense Fund; and Roger Cooke, Resources for the Future. The session examined the implications of assessing and valuing climate change impacts for climate policy analysis and design, including the following implications: for design and benefit-cost analysis of emission reduction policies, for addressing equity and natural capital impacts, for choice of policy targets for cost-effectiveness analysis, and for managing climate risks.

Implications for Design and Benefit-Cost Analysis of Emission Reduction Policies

Dr. Raymond Kopp focused his presentation on the needs of three classes of policymakers and how IAMs might meet those needs. Specifically, he looked at legislative policymakers, including the U.S. Congress; international policymakers, including the U.S. Executive Branch; and regulatory agencies, including the U.S. EPA.

Dr. Kopp noted that legislative policymakers never ask for the social cost of carbon or the benefit-cost ratio of a given carbon price. Instead, legislative policymakers are interested in: how climate change will affect the world, the country, and their constituents; worst case scenarios; how adaptation can help; how their constituents will benefit from mitigation; the cost of mitigation; the distribution of costs to their constituents; ways to lower costs; and their constituents' willingness-to-pay to avoid damages.

Dr. Kopp then presented the areas of interest and questions of international policymakers. Past and current areas of interest include: estimates of damage such as the Stern Review, with particular interest in well-defined sector- and region-specific impacts; estimates of mitigation costs; and distribution of costs. New questions include: how to measure individual country levels of effort; how to measure incremental cost; how to estimate realistic offset supply curves that address cost and timing; how a global carbon market would affect international trade and investment; and how large-scale "green growth" policies would affect trade and investment.

Next, Dr. Kopp noted that regulatory requirements of executive orders seem to be the sole reason the Interagency Working Group developed the SCC estimates and continues to refine them. He explained that there may be roles for IAMs to play in regulatory design other than in regulatory impact analysis, but that the role will be specific to the regulation in question.

Dr. Kopp outlined the information likely to be of future value to legislation and foreign policy. This information includes detail on the distribution and severity of damages; characterization of adaptation potential to lower damages; and estimates of damage sensitivity to the speed of climate change. Finally,

Dr. Kopp highlighted the missing element in current SCC analysis: the complete lack of non-use values, bequest values, existence values, and passive use values. He noted that these methods of non-market valuation are those classically used in intra- and inter-generational valuation.

During the question and answer session, a couple of participants asked about breaking down and allocating the social cost of carbon to more meaningful units, such as domestic SCC and international SCC or present generation costs and future generation costs, to better answer the questions posed by policymakers. Another participant noted that the interagency group made the policy decision to focus on the global SCC and intentionally did not break it down.

A third participant suggested that while there will certainly be costs to climate action, these costs are mitigated by phasing in policy rather than doing an overnight overhaul and encouraging market innovation under constraints. She further noted that past actions have not been particularly costly. Dr. Kopp re-emphasized that when costs do enter, the distribution of costs is very important politically. Finally, a participant asked how to meaningfully consider the willingness to pay for species extinction of 10-25 percent of species. Dr. Kopp explained the need to clearly articulate the consequences so that people can value them.

Implications for Addressing Equity and Natural Capital Impacts

Dr. Geoffrey Heal then presented the issues of intragenerational equity and natural capital. Intergenerational equity is bound up with the pure rate of time preference. Both inter- and intra-generational equity are affected by the elasticity of the marginal utility of consumption, designated in this discussion as η. Dr. Heal presented two contradictory implications of equity. First, he showed how higher intergenerational equity means a higher value for η, which produces a higher discount rate, and therefore less concern for future generations and less inclination to act on climate change. Second, he showed how a higher emphasis on intragenerational distributional equity leads to a higher value placed on the losses of poor countries, and therefore more inclination to act on climate change. Dr. Heal explained that in most aggregated IAMs, only the first implication is modeled, so that a higher intragenerational concern leads to less inclination to deal with climate change. He noted that a disaggregated model would incorporate the counter-argument.

Next, Dr. Heal considered natural capital. He noted that poor countries are more dependent on the services of natural capital than rich countries. He proposed that there is some minimum level of natural capital needed to maintain positive welfare. Dr. Heal then explained that running DICE with this objective makes a significant difference to model results.

Dr. Heal concluded first that IAM formulations need to separate the three distinct roles of η: affecting intergenerational choices, intragenerational choices, and risk aversion. Second, he concluded that models need to distinguish environmental services from manufactured goods and rich groups from poor groups.

During the question and answer session, one participant suggested moving away from the Ramsey equation, as it builds in aggregation. Dr. Heal agreed, noting that the Ramsey equation promotes

thinking as a representative individual and therefore neglects equity. He explained that the use of distributional rates is returning after having fallen out of use.

Another participant encouraged disaggregating climate change drivers from intragenerational equity drivers, so that it is clear model results are motivated by climate change. He noted that other policy instruments exist to deal with inequality. Dr. Heal agreed, noting that international agreements have fallen apart due to attempts to address other, unrelated issues in the same policy. A last participant commented on the outdated nature of the economic methods used in climate economics. He noted that the Ramsey paradigm is 70 years old and that climate change economics is 30 years old. He wondered why there has not been more progress. Dr. Heal explained that, until recently, climate economics has been a thin field with few people.

Implications for Choice of Policy Targets for Cost-Effectiveness Analysis

Dr. Nathaniel Keohane then gave a presentation on the implications for choice of policy targets for cost-effectiveness analysis. Dr. Keohane started by pointing out that the SCC is not a cost-effectiveness measure as it does not incorporate the cost of achieving a goal. Instead, he suggested the SCC could be used in the "spirit" of cost-effectiveness and in establishing consistency.

Dr. Keohane suggested that choosing the appropriate type of target (e.g., emissions target, risk target) is critical. He also suggested that what other countries do is important. Dr. Keohane noted that the United Kingdom uses a cost-based shadow price measure. He then presented some concrete ideas for what a cost-effectiveness approach would look like. First, he suggested a cost-based approach where shadow prices are set to achieve a global scenario (e.g., 450 ppm CO_2e or 2°C warming) or a range of national targets. Second, he suggested a risk-based approach such as a risk management framework or a direct valuation of the shift in the distribution. He underlined the common thread in these options of marginal analysis, noting that these options are not mutually exclusive with each other or with a damages-based SCC approach. He concluded that some number is better than no number but several numbers may be better than one, depending on the intended use.

Dr. Keohane then discussed the role of the current damages-based SCC. He suggested that the SCC should not be used as a measure of policy stringency or as the sole input into RIA. Instead, the SCC should be used to ensure consistency across regulatory agencies and as one of many inputs into RIA. He noted that the SCC has been used in other proceedings as a tangible, credible measure of the value of carbon. He explained that these uses show that numbers will be used, that the SCC establishes the principle that marginal damages are real and can be quantified, and that whether or not the current estimate is too low, it is still much higher than $0.

Finally, Dr. Keohane noted the disconnect between economics and natural science. He suggested that the models be unpacked and searched for inputs that do not match the natural science. He highlighted the damage functions as a likely candidate for improvement. He finished by asking how the results of the workshop will be incorporated into a process going forward.

During the question and answer session, Dr. Keohane noted that the SCC would be approximately three times larger if the goal was stabilization. One participant suggested that cumulative emissions would be

a more appropriate metric than emissions concentration. Another participant commended the topic of the presentation, underlining the importance of cost-effectiveness questions. He suggested that there are more effective communication tools, such as illustrating how New York will begin to look like DC, and DC like Florida under the effects of climate change.

Implications for Managing Climate Risks

Dr. Roger M. Cooke concluded the presentation portion of Session 4 with his presentation on managing climate risks. Dr. Cooke presented from the perspective of mathematical risk analysis. Instead of modeling impacts around a risk-averse representative customer, he suggested climate change should be managed by risk-constrained optimization.

Dr. Cooke discussed testing current models using stress tests. He presented an example by stress testing the DICE model, showing the model's questionable results when pushed outside of reasonable parameter ranges. Dr. Cooke then discussed the benefit of exploring canonical variations to see if other simple model forms have structurally different behavior. Again, he presented an illustrative example using the LotkaVolterra model.

Finally, Dr. Cooke discussed the concepts of inner and outer measures. He explained that there are two ways to estimate a complicated, or "ugly", sum. First, an inner measure attempts to quantify different simpler subsets of the sum, with the hope of capturing enough subsets that they add up to the total. An outer measure estimates a simple sum greater than the total, knowing the goal sum lies within. It tries to narrow the estimate until it approximates the goal sum. If a set is measureable, the inner measure will converge with the outer measure. He followed this explanation with a slide presenting the Yale G-Econ database as an example. He then showed a series of regressions and a plot demonstrating an "outer" measure with impacts dependent on factors other than average temperature. Dr. Cooke concluded by emphasizing the need to address model uncertainty and the need to converge the "inner" and "outer" damage models.

During the question and answer session, one participant asked how to conduct risk-constrained optimization given uncertainty regarding the distribution of outcomes. Dr. Cooke explained that the models should be fit to structured expert judgments. Another participant commended the idea of using expert input but questioned the econometric validity of Dr. Cooke's regressions without numerous other variables. Dr. Cooke clarified that the regressions were merely an illustration, to be improved upon, of how one might construct an outer measure.

Session 4 Discussion

Following the questions on Dr. Cooke's presentation, the discussion portion of Session 4 began. One participant pointed out that the interagency process did produce a range of estimates and questioned why the focus has been on the central estimate rather than the full range. The panel concurred, emphasizing the need to communicate the full range. Dr. Heal suggested the interagency-produced range provides a lower bound to a much wider and higher range. Another participant emphasized a focus on targets with SCC estimates developed to produce that target. For example, the participant cited a study that concluded a $75-$100 shadow price would be needed to reduce emissions by 17

percent by 2020. However, a member of the panel emphasized that this may not be possible, given that there is no nationally agreed-upon emissions goal in the United States against which policies can be evaluated. Until that happens, analysts must use the tools available to them to evaluate the impacts of regulations, one of which is benefit-cost analysis.

A third participant criticized funding agencies for funding only the incremental development of existing IAMs. He suggested this type of funding decision prevented new modelers from entering the field and developing new and different models as discussed at the workshop. However, another participant suggested this type of funding decision may allow agencies to spend limited resources in areas with greater payoff.

During the session, participants discussed how best to meaningfully use the range of SCC estimates. Dr. Cooke suggested the range as an indication of where the central value might lie in the future. Dr. Keohane questioned the value of models, such the Department of Transportation's Volpe model that require a single input. He suggested developing creative ways to visually communicate the data, results, and tables presented by the interagency working group. Another participant emphasized the importance of communicating the appropriate degree of precision when presenting SCC estimates by rounding appropriately. For example, reporting the SCC with multiple significant figures gives a highly overconfident impression of the precision of these estimates. A different participant cautioned against presenting subjective judgments objectively, as a number. He suggested communicating SCC subjectivity to decision makers and perhaps relying more on the statutory process than the regulatory process.

Dr. Keohane suggested that modelers are not limited to pursue one valuation method or another. Instead, he commented, if the SCC is pursued, efforts like this workshop exist to try to unpack the problems. He highlighted the issues of communication; conveying uncertainty; combining and enriching the SCC with other processes and measures (e.g., risk management); using qualitative analysis; and using natural units analysis. Ultimately, if one number is needed, he suggested that every effort be made to identify what it should be, but that it should also be enriched with other numbers.

Session 5: Workshop Wrap-up

The workshop concluded with summary comments by representatives from the U.S. Department of Energy and the U.S. Environmental Protection Agency. First, Dr. Rick Duke, the DOE Deputy Assistant Secretary for Climate Policy, presented his closing remarks. He commented that the discussion had been passionate, rich, and complex, doing justice to the topic. He noted that the SCC is a useful step to examine the full range of goal-directed options in an economically sensible way, particularly important to stimulate regulatory action.

Next, Dr. Duke emphasized that this workshop demonstrates DOE's and Secretary Chu's commitment to integrity in science, economics, and policy. Keeping in that theme, Dr. Duke acknowledged that the models used by the interagency process use reduced-form damage functions with simple functional forms. He said that he looked forward to improving them over time. He also noted that DOE is funding work with the higher resolution models, such as GCAM and IGSM. He highlighted the radically different

nature of these models, remarking that perhaps we have been "looking for the keys under one streetlight" and instead, "need to build more streetlights." Dr. Duke echoed Dr. Cooke's proposal to optimize risk under constraint and Dr. Heal's notion of the deeply imperfect substitutability of natural capital.

Dr. Duke then suggested that even with the most comprehensive suite of bottom-up policies based on the SCC, the complexities may prevent the attainment of adequate abatement goals. He closed with a comment on the workshop participation. He noted the thin and disjointed nature of the field and expressed his pleasure at seeing such good attendance at the workshop. He explained that the interagency process has encouraged continued refinement of the SCC and expressed his hope that the workshop attendees would continue to be involved in the refinement process.

Finally, Dr. Al McGartland, Office Director for EPA's NCEE, presented his closing remarks. Dr. McGartland started by remarking the conversation had been stimulating and thought provoking. He noted that he thought the idea of unpacking the models and identifying areas for improvement makes sense. He then shared some broader thoughts on the importance and difficulty of cost-benefit analysis over the course of EPA's history. He noted the significant traction gained by CBA during air toxics analysis, particulate matter analysis, and recycling versus disposal analysis.

He explained that despite the inherent difficulties and uncertainties involved, for most environmental problems, economists tend to band together and "circle the wagons" in support of doing CBA. He then polled the participants on how they feel about the SCC exercise. He asked for a show of hands for whether or not they would pursue the SCC exercise if they were decision makers. A few participants indicated they would 'pull the plug' on the SCC exercise altogether. No one supported forging ahead full speed and 'circling the wagons' without better communication of the great uncertainties involved in such estimates. Most of the participants indicated that they would follow a middle path, to continue to cautiously, bravely pursue the SCC exercise without 'circling the wagons.'

After Dr. McGartland concluded his comments, one of the workshop participants asked how this workshop will fit into the two-year plan and how the participants could be involved. Dr. McGartland responded that the first product of the workshop would be a workshop report with a summary of the proceedings. He noted that the next steps in the interagency process have not yet been completely defined at this point, but he hoped the interagency group would reconvene in the timeframe outlined in the 2010 report. He emphasized that EPA is solidly supportive of engaging the public generally and the research community specifically. Finally, he noted that the second conference focused on damage functions will take place in late January.