WORKSHOP PROCEEDINGS

Assessing the Benefits of Avoided Climate Change: Cost-Benefit Analysis and Beyond

March 16-17, 2009
Washington, DC

May 2010

PEW CENTER ON Global CLIMATE CHANGE

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Energy Foundation
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San Francisco, CA 94111

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The complete workshop proceedings, including video of 17 expert presentations, this summary report, and individual off-prints of expert papers are available free of charge from the Pew Center on Global Climate Change at http://www.pewclimate.org/events/2009/benefitsworkshop.

May 2010

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Table of Contents

FOREWORD

The Pew Center on Global Climate Change is pleased to present the proceedings of its March 2009 workshop, *Assessing the Benefits of Avoided Climate Change: Cost-Benefit Analysis and Beyond*. Even though significant uncertainties about future climate impacts remain, government decision-making requires consideration of all economic costs and benefits if policies are to maximize the social benefits of regulatory decisions. This workshop was convened to explore the current state of the art in analyzing climate-related benefits, its strengths and weaknesses, and ways to improve it.

Placing a value on the benefits of reducing greenhouse gas emissions is quickly moving from the pages of academic journals and IPCC reports to the front burner in regulatory decision making. This policy revolution began with the growing acceptance of the science linking climate change to adverse impacts on public health and welfare and the potential catastrophic risks associated with continued greenhouse gas emissions. In the absence of federal action to limit climate change, concerned citizens and state governments intervened through the courts. The 2007 decision of the Supreme Court in Massachusetts v. EPA set down a clear marker that the consequences of climate change cannot simply be disregarded in regulatory decisions. Even without new climate legislation, therefore, limited steps to reduce greenhouse gas emissions have begun to unfold through individual regulatory decisions across a number of agencies.

When I was in government, I managed the writing of regulations, including the acid rain trading program and the phase out of CFCs. A key element in these and all rules developed across the government is the use of cost-benefit analysis (CBA). Yet the benefits from reducing greenhouse gas emissions have been ignored, until recently. In 2009, DOE used CBA to account for the benefits of reducing greenhouse gas emissions in setting efficiency standards for beverage vending machines. NHTSA and EPA followed suit in setting efficiency standards and greenhouse gas limits for light-duty vehicles. Now that the benefits are being considered, we must ensure that the estimates adequately reflect the risks of climate change.

As important as individual regulatory decisions may be, they are no substitute for major new legislation to limit climate change. Congress and the Obama administration are grappling with how to bring about the necessary shift to a low-carbon economy. Yet in these difficult economic times, efforts to put a price on carbon are met with objections that it is too expensive. The best counter to this claim is that inaction is also very expensive, and the risk of intolerable outcomes is much greater if we don't act to limit climate change. The need for a better quantification of the benefits of greenhouse gas reductions that incorporates the risks of inaction is thus urgent.

The government's initial effort to account for climate-related benefits in regulatory decisions is a step in the right direction. But much work is still needed to develop sound estimates of those benefits. I hope that these proceedings will clarify this need for policy makers and identify some practical steps forward. I thank all of the workshop speakers and participants, especially the background paper authors, who helped make the workshop a success.

Eileen Claussen
President
Pew Center on Global Climate Change

Agenda

Assessing the Benefits of Avoided Climate Change

Hyatt Regency on Capitol Hill, Washington, DC
March 16-17, 2009

The U.S. government is considering a range of near-term actions to address the risks of climate change. The Obama administration and key members of Congress intend to make climate legislation a top priority this year. The earliest action, however, may come from federal agencies being pressured by the courts and states to consider limiting CO_2 emissions under existing legislative authority. A key element of federal rulemaking is assessing the costs and benefits of proposed policies. While the costs of reducing greenhouse gas emissions have received much attention from analysts and policymakers, far less attention has been directed at quantifying the benefits of such reductions. In spite of remaining uncertainties, the analytical community should offer practical guidance for informing near-term decisions. Drawing from the environmental economics, impacts, vulnerability, and risk assessment communities, this workshop will consider what useful insights can be gleaned now about quantifying the benefits of reducing greenhouse gas emissions. The workshop's objectives are to develop a set of practical recommendations that decision makers can employ in the near-term and to outline a research path to improve decision making tools over time.

DAY 1: Symposium – Assessing the benefits of avoided climate change in government decision making

8:00-8:30 AM Continental Breakfast

8:30-8:45 AM Opening Remarks
Eileen Claussen, President, Pew Center on Global Climate Change

8:45-9:30 AM Keynote Address
Dina Kruger, Director, Climate Change Division, Office of Air and Radiation, U.S. EPA

9:30-11:00 AM Session 1: Perspectives on Government Decision Making for Climate Change
Moderator: Steve Seidel, Vice President for Policy Analysis, Pew Center

- Martha Roberts, EDF: *Incorporating the benefits of climate protection into federal rulemaking*
- Christopher Pyke, CTG Energetics: *A proposal to consider global warming under NEPA*
- James Lester/Joel Smith, Stratus Consulting: *Case studies on government decisions to limit greenhouse gas emissions – California, Australia, United Kingdom*
- Paul Watkiss, Paul Watkiss Associates: *Social cost of carbon estimates and their use in UK policy*

11:00-11:15 AM Coffee Break

11:15 AM-12:45 PM Session 2: Challenges to Quantifying Damages from Climate Change
Moderator: Jeremy Richardson, Senior Fellow for Science Policy, Pew Center

- Mike MacCracken, Climate Institute: *Overview of challenges to quantifying impacts*
- Kristie Ebi, ESS, LLC: *Social vulnerability and risk*
- Tony Janetos, Joint Global Change Research Institute: *Ecosystems and species*
- Jon O'Riordan, University of British Columbia: *Valuation of natural capital*

12:45 PM-2:00 PM Lunch

Introduction by Jay Gulledge, Senior Scientist/Science & Impacts Program Manager, Pew Center

- 1:15-1:45 PM Lunch speaker
  Gary Yohe, Wesleyan University: *The long view: developing a new decision making framework based on the IPCC's 'iterative risk management' paradigm*

2:00-3:30 PM Session 3: The Role of Uncertainty in Assessing the Benefits of Climate Policy

Moderator: Jay Gulledge, Senior Scientist/Science & Impacts Program Manager, Pew Center

- Brian O'Neill, NCAR: *Uncertainty and learning – implications for climate policy*
- Joel Smith, Stratus Consulting: *Dangerous climate change: an update of the IPCC reasons for concern*
- Michael Mastrandrea, Stanford University: *Assessing damages with integrated assessment models*
- Chris Hope, University of Cambridge: *Social cost of carbon and optimal timing of emissions reductions under uncertainty*

3:30-3:45 PM Coffee Break

3:45-5:15 PM Session 4: Advances in the Economic Analysis of the Benefits of Climate Policy

Moderator: Liwayway Adkins, Senior Fellow, Economics, Pew Center

- Steve Rose, EPRI: *Federal decision making on the uncertain impacts of climate change: working with what you have*
- Richard Howarth, Dartmouth College: *The need for a fresh approach to climate change economics*
- David Anthoff, ESRI: *National decision making on climate change and international equity weights*
- Steve Newbold, U.S. EPA: *Climate response uncertainty and the expected benefits of greenhouse gas emissions reductions*

5:15-5:30 PM Closing Remarks

Janet Peace, Vice President for Markets and Business Strategy, Pew Center

5:30-7:30 PM Dinner Reception

DAY 2: Expert working group discussion to formulate recommendations for decision makers and to outline near-term research priorities

8:00-8:30 AM Continental Breakfast

8:30-8:45 AM Synthesis of Day-1 Discussion and Orientation for Day-2

Jay Gulledge, Senior Scientist/Science & Impacts Program Manager, Pew Center

8:45-11:45 AM Moderated Roundtable Discussion

Moderators: Steve Seidel, Vice President for Policy Analysis and Janet Peace, Vice President for Markets and Business Strategy, Pew Center; Rapporteurs: Pew staff

11:45 AM-12:00 PM Closing Remarks and Next Steps

Noon: Adjourn

Participant List

Assessing the Benefits of Avoided Climate Change

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Liwayway Adkins	Pew Center on Global Climate Change
David Anthoff	The Economic & Social Research Institute
Vicki Arroyo	Georgetown State & Federal Climate Resource Center
Alex Barron	US Congress
Rona Birnbaum	US Environmental Protection Agency
Jason Bordoff	The Brookings Institution
Mark Borsuk	Dartmouth College
Sharon Burke	Center for a New American Security
Stephen Caldwell	Pew Center on Global Climate Change
Margaret Carreiro	University of Louisville
Kate Cecys	Pew Center on Global Climate Change
Eileen Claussen	Pew Center on Global Climate Change
Rob Cobbs	US Congress
Daniel Cole	Indiana University School of Law
Francisco de la Chesnaye	Electric Power Research Institute
Benjamin DeAngelo	US Environmental Protection Agency
Stephen DeCanio	University of California, Santa Barbara
Kristie Ebi	ESS, LLC
Erika Engelhaupt	Environmental Science & Technology
Charles Griffiths	US Environmental Protection Agency
Britt Groosman	Environmental Defense Fund
Jay Gulledge	Pew Center on Global Climate Change
Gary Guzy	APX, Inc.
Richard Harris	National Public Radio
Danny Harvey	University of Toronto
Reid Harvey	US Environmental Protection Agency
Pat Hogan	Pew Center on Global Climate Change
Heather Holsinger	Pew Center on Global Climate Change
Chris Hope	University of Cambridge
Richard Howarth	Dartmouth College
Judson Jaffe	US Treasury, Office Environment & Energy
Anthony Janetos	Joint Global Change Research Institute
Daniel Johansson	Gothenburg & Chalmers Universities
Rob Johansson	Congressional Budget Office
Laurie Johnson	Natural Resources Defense Council
Tim Juliani	Pew Center on Global Climate Change
Jim Ketcham-Colwill	US Environmental Protection Agency
Elizabeth Kim	Pew Center on Global Climate Change
Charles Kolstad	University of California
Elizabeth Kopits	Council of Economic Advisors
Carolyn Kousky	Resources for the Future

Dina Kruger	US Environmental Protection Agency
Peter Larsen	Lawrence Berkeley National Laboratory
Linda Lawson	U.S. Department of Transportation
Jessica Leber	ClimateWire
Evan Lehmann	ClimateWire
James Lester	Stratus Consulting
Michael Livermore	New York University School of Law
Michael MacCracken	Climate Institute
Christa Marshall	ClimateWire
Wade Martin	California State University
Michael Mastrandrea	Stanford University
Will McDowall	National Round Table on the Environment and the Economy
James McMahon	Lawrence Berkeley National Laboratory
Bryan Mignone	The Brookings Institution
Christopher Moore	US Environmental Protection Agency
Adele Morris	The Brookings Institution
John Morton	The Pew Charitable Trusts
Anna Motschenbacher	Pew Center on Global Climate Change
Steve Newbold	US Environmental Protection Agency
Daniel Newlon	National Science Foundation
Robert O'Connor	National Science Foundation
Brian O'Neill	National Center on Atmospheric Research
Jon O'Riordan	University of British Columbia
Namrata Patodia	Pew Center on Global Climate Change
Janet Peace	Pew Center on Global Climate Change
Vicky Pope	Met Office Hadley Centre
Chris Pyke	CTG Energetics, Inc.
Jeremy Richardson	Pew Center on Global Climate Change
Martha Roberts	Environmental Defense Fund
Steven Rose	Electric Power Research Institute
David Rosner	National Commission on Energy Policy
Matthias Ruth	University of Maryland
Marcus Sarofim	AAAS Science & Technology Policy Fellow
Josh Schimel	University of California
Steve Seidel	Pew Center on Global Climate Change
Robert Shackleton	Congressional Budget Office
Kristen Sheeran	E3 Network
Joel Smith	Stratus Consulting Inc.
Tom Steinfeldt	Pew Center on Global Climate Change
Tara Ursell	Pew Center on Global Climate Change
Bob Vallario	US Department of Energy
Stephanie Waldhoff	US Environmental Protection Agency
James Warner	Pew Center on Global Climate Change
Paul Watkiss	Paul Watkiss Associates
Michael Wolosin	The Nature Conservancy
Gary Yohe	Wesleyan University

Speaker Biographies

Assessing the Benefits of Avoided Climate Change

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Featured Speakers

Eileen Claussen is the President of the Pew Center on Global Climate Change and Strategies for the Global Environment. Ms. Claussen is the former Assistant Secretary of State for Oceans and International Environmental and Scientific Affairs. She served as a Special Assistant to the President and Senior Director for Global Environmental Affairs at the National Security Council and as Chairman of the United Nations Multilateral Montreal Protocol Fund. Ms. Claussen was also Director of Atmospheric Programs at the U.S. Environmental Protection Agency. She is a member of the Council on Foreign Relations, the Singapore Energy Advisory Committee, and the Ecomagination Advisory Board. Ms. Claussen is the recipient of the Department of State's Career Achievement Award and the Distinguished Executive Award for Sustained Extraordinary Accomplishment. She also served as the Timothy Atkeson Scholar in Residence at Yale University.

Dina Kruger is Director of the Climate Change Division in the Office of Air and Radiation of the U.S. Environmental Protection Agency. Ms. Kruger is responsible for a wide range of programs and analyses dealing with climate change policy, economics, mitigation technologies, science and impacts, and communication. She is currently managing the development of a U.S. EPA rulemaking on the mandatory reporting of greenhouse gases and is providing economic, technical and scientific support to the ongoing rulemakings in the Office of Air and Radiation and the Office of Water. Ms. Kruger directs the EPA's domestic partnership programs on methane and fluorinated gases and the Methane to Markets Partnership, an international initiative aimed at the development of cost-effective methane recovery and use projects that involves developed and developing countries as well as the private sector. She also manages preparation of the U.S. National Inventory of Greenhouse Gases and Sinks, which is submitted annually to the United Nations Framework Convention on Climate Change, and since 1988 has served as an elected member of the Intergovernmental Panel on Climate Change's Task Force Bureau on Greenhouse Gas Inventories. Ms. Kruger has an M.A. from the Energy and Resources Group at the University of California, Berkeley, and a B.A. from the University of Washington.

Gary W. Yohe is the Woodhouse/Sysco Professor of Economics at Wesleyan University and Visiting Professor of Economics at the Yale School of Forestry and Environmental Studies. Most of his work has focused attention on the mitigation and adaptation/impacts sides of the climate issue. Dr. Yohe served as convening lead author for one chapter in the "Response Options Technical Volume" of the Millennium Ecosystem Assessment. His call for a risk management approach to climate policy was adopted last fall in the Synthesis Report of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. He has been a senior member of the IPCC since the mid 1990s, serving as a lead author for four different chapters in the Third Assessment Report and as convening lead author for the last chapter of the contribution of Working Group II to the Fourth Assessment Report. He sits on the New York Panel on Climate Change, the Committee on the Human Dimensions of Global Change for the National Research Council, and the Adaptation Panel of the National Academy of Science initiative on America's Climate Choices. He was educated at the University of Pennsylvania and received his Ph.D. in economics from Yale University in 1975.

Panelists

David Anthoff is an environmental economist working on climate change. He is a post doctoral associate of The Economic and Social Research Institute (Dublin) and a freelance consultant on climate change issues. He is working with the integrated assessment model *FUND*. Mr. Anthoff was a visiting research fellow at the Smith School of Enterprise and the Environment at the University of Oxford in the fall of 2008. He is doing a Ph.D. in environmental economics at the International Max Planck Research School on Earth System Modeling and the Research Unit Sustainability and Global Change at Hamburg University. He holds an M.Sc. in environmental change and management from the Environmental Change Institute at the University of Oxford. Previously, he studied philosophy in Munich and Oxford and obtained an M.Phil. in philosophy, logic, and theory of science from Ludwig-Maximilians-Universität München. He lives and works in Munich, Germany.

Kristie L. Ebi is Executive Director of the Technical Support Unit for Working Group II (Impacts, Adaptation, and Vulnerability) of the Intergovernmental Panel on Climate Change. Prior to this position, she was an independent consultant. She has been conducting research on the impacts of and adaptation to climate change for more than a dozen years, including on extreme events, thermal stress, food-borne safety and security, and vector-borne diseases. She has worked with the World Health Organization, the United Nations Development Programme, the U.S. Agency for International Development, and others on implementing adaptation measures in low-income countries. She facilitated adaptation assessments for the health sector for the states of Maryland and Alaska. She was a lead author of the human health chapter of the IPCC Fourth Assessment Report, and the human health chapter of the U.S. Climate Change Science Program's Synthesis and Assessment Product, *Analyses of the Effects of Global Change on Human Health and Welfare and Human Systems.* Dr. Ebi's scientific training includes a Ph.D. and a Masters of Public Health in epidemiology, an M.S. in toxicology, and two years of postgraduate research at the London School of Hygiene and Tropical Medicine.

Chris Hope is Reader in Policy Modeling at Judge Business School. He is a member of the editorial board of the journals *Integrated Assessment* and *Transport Policy*. He was lead author and review editor for the Third and Fourth Assessment Reports of the Intergovernmental Panel on Climate Change. He is an invited member of OFGEM's Environmental Economists Panel. Chris was the specialist advisor to the House of Lords Select Committee on Economic Affairs Inquiry into aspects of the economics of climate change and an advisor on the PAGE model to the Stern Review on the Economics of Climate Change. In 2007, he was awarded the Faculty Lifetime Achievement Award from the European Academy of Business in Society and the Aspen Institute. His research interests involve numerical information in public policy and the integrated assessment modeling of climate change, and he has published extensively in books and peer-reviewed journals.

Richard Howarth is the Pat and John Rosenwald Professor at Dartmouth College and serves as Editor-in-Chief of *Ecological Economics.* He is an environmental and ecological economist who studies the interface between economic theory and the ecological, moral, and social dimensions of environmental issues. His topical interests focus on energy use, climate change, and ecological conservation. Professor Howarth graduated *summa cum laude* from the Biology and Society Program at Cornell University (A.B., 1985) and holds an M.S. in Land Resources from the University of Wisconsin-Madison (1987). He earned his Ph.D. from the Energy and Resources Group at the University of California at Berkeley (1990), where he collaborated with Richard B. Norgaard on the economics of natural resources and sustainable development. Before joining Dartmouth's faculty in

1998, Professor Howarth held research and teaching positions at the Lawrence Berkeley National Laboratory (1990-1993) and the University of California at Santa Cruz (1993-1998).

Anthony Janetos is the Director of the Joint Global Change Research Institute, a joint venture between the Pacific Northwest National Laboratory and the University of Maryland. Dr. Janetos has many years of experience in managing scientific and policy research programs on a variety of ecological and environmental topics, including air pollution effects on forests, climate change impacts, land-use change, ecosystem modeling, and the global carbon cycle. He was also a co-convening lead author of the U.S. Climate Change Science Program's Synthesis and Assessment Product 4.3, *Climate Change Impacts on Agriculture, Land Resources, Water Resources, and Biodiversity*. Dr. Janetos earned Ph.D. and master's degrees in biology from Princeton University and a bachelor's degree (*magna cum laude*) from Harvard College.

James Lester, associate with Stratus Consulting, has been researching and monitoring global, federal, and state climate legislation and the development of related emissions markets. He has experience researching and analyzing federal, state, and local renewable energy and energy efficiency activities for the U.S. Environmental Protection Agency and other government agencies. As a research analyst at the World Resources Institute, Mr. Lester performed financial and economic analyses for the Green Power Market Development Group's initiative, which increased corporate purchasing of renewable energy in both the United States and Europe. He researched and analyzed macroeconomic and general equilibrium models used to identify economic effects of federal climate legislation. As a staff assistant for U.S. Congressman Dennis Moore, he researched economic and environmental legislative issues. Mr. Lester holds a master's degree in environmental economics from the University of Colorado and a bachelor's degree in economics from the University of Kansas.

Michael MacCracken is Chief Scientist for Climate Change Programs with the Climate Institute in Washington, D.C. Dr. MacCracken conducted research on climate change and air pollution with the University of California's Lawrence Livermore National Laboratory, evaluating the climatic effects of volcanic eruptions, greenhouse gases and nuclear war. From 1993-2002, he was detailed from LLNL as senior global change scientist to the U.S. Global Change Research Program, serving as the first executive director of the Interagency Coordinating Office from 1993-1997 and then as executive director of the National Assessment Coordination Office from 1997-2001. He also helped coordinate the U.S. government review of the Second and Third Assessment Reports of the Intergovernmental Panel on Climate Change. Since joining the Climate Institute in 2002 on a voluntary basis, his activities have included participation in the Arctic Climate Impact Assessment, serving as review editor for the North America chapter of the IPCC's Fourth Assessment Report, election as president of the International Association of Meteorology and Atmospheric Sciences, and service on the executive committees of the International Union of Geodesy and Geophysics, and the Scientific Committee on Oceanic Research. He received a Ph.D. in applied science from the University of California Davis/Livermore in 1968 and a B.S. in engineering from Princeton University in 1964.

Michael D. Mastrandrea is a Research Associate at the Stanford University Woods Institute for the Environment and a lecturer in the Emmett Interdisciplinary Program in Environment and Resources. His research interests include integrated modeling of the climate and society as a tool for international and domestic policy analysis; climate change impacts and vulnerability assessment in California and worldwide based on observed climate data and climate model projections; and treatment of uncertainty in climate change projections and climate policy decision making. His work has been published in several journals, including *Science* and *Proceedings of the National Academy of Sciences*, and he is a co-author of chapters on key vulnerabilities and climate risks and long-term mitigation strategies for the 2007 Intergovernmental Panel on Climate Change Fourth Assessment Report. He also serves on the Editorial Board for the journal *Climatic Change*. He received a Ph.D. from the Interdisciplinary Graduate Program in Environment and Resources and a B.S. in biological sciences, both from Stanford University.

Stephen C. Newbold is a policy analyst at the U.S. Environmental Protection Agency's National Center for Environmental Economics. Dr. Newbold's responsibilities include reviewing and providing technical advice for regulatory impact analyses, including benefit-cost analyses, conducted by U.S. EPA program offices in support of new regulations, and maintaining an independent research agenda. His main areas of interest include ecological modeling, ecosystem valuation using linked ecological or bio-economic models and revealed preference valuation models, systematic conservation planning, and methods of benefits estimation for climate change policies. He received a Ph.D. in ecology from the University of California, Davis.

Brian O'Neill is a Scientist III in the Institute for the Study of Society and Environment at the National Center for Atmospheric Research. He also leads the Population and Climate Change Program at the International Institute for Applied Systems Analysis in Laxenburg, Austria. Brian's research interests are in the field of integrated assessment modeling of climate change, which links socio-economic and natural science elements of the climate change issue in order to address applied, policy-relevant questions. Particular areas of focus include the relationship between demographic change and greenhouse gas emissions, the characterization of uncertainty and its role in decision analysis, and scenario analyses linking long-term climate change goals to shorter-term actions. He has also served as a lead author for the Intergovernmental Panel on Climate Change's Fourth Assessment Report in a volume on impacts, adaptation and vulnerability (Working Group II), and for the Millennium Ecosystem Assessment in a volume on scenarios. He holds a Ph.D. in earth systems science and an M.S. in applied science, both from New York University.

Jon O'Riordan is currently an adjunct professor in the Faculty of Interdisciplinary Studies at the University of British Columbia. Dr. O'Riordan is also a policy advisor to the Climate Change Adaptation Team centered at Simon Fraser University in Vancouver, British Columbia. He has worked in the public sector all his professional life, first in the federal government in water resource management and later in the British Columbia provincial government in the Ministry of Environment. He was appointed Deputy Minister of the Ministry of Sustainable Resource Management in 2001 and retired from the public service in 2004. He earned a doctorate at the University of British Columbia in water resource management in 1968.

Christopher Pyke is the national director of Climate Change Services for CTG Energetics, Inc. He has worked on issues associated with climate change mitigation, impact assessment, and adaptation for the last 15 years. His work currently focuses on helping clients use buildings and land use to reduce greenhouse gas emissions and prepare for changing climatic conditions. Dr. Pyke is a member of the Scientific and Technical Advisory Committee to the U.S. Environmental Protection Agency's Chesapeake Bay Program and the greenhouse gas Advisory Committee for the ANSI Standard 14065. Prior to joining CTG, Dr. Pyke served as a scientist with the U.S. EPA and a postdoctoral fellow at the National Center for Ecological Analysis and Synthesis in Santa Barbara, California. Dr. Pyke holds a Ph.D. and M.A. in geography from the University of California, Santa Barbara and a B.S. in geology (*magna cum laude*) from the College of William and Mary.

Martha Roberts is an Economic Policy Analyst in Environmental Defense Fund's Rocky Mountain Office. Her work includes research on the cost of inaction on global warming, analysis of the need to incorporate the social cost of carbon into federal cost-benefit analyses, and outreach on the green job opportunities available in a low-carbon economy. Along with Nancy Spencer, Ms. Roberts was the author of the recent EDF report, "Carbon Counts: Incorporating the Benefits of Climate Protection into Federal Rulemaking." Ms. Roberts received M.S. and B.S. degrees in earth systems from Stanford University.

Steven Rose is a senior economist at the Electric Power Research Institute. His current research focuses on long-run modeling of climate change drivers, mitigation, and potential risks. He also models the economics of land-use and bioenergy as it relates to domestic and international climate change policy. Before joining EPRI in October 2008, Dr. Rose served as a senior research economist on climate change at the U.S. Environmental Protection Agency, where he was a senior technical advisor for domestic policy-making and international negotiations and actively engaged in research as well as scientific assessments. He was a lead author for the IPCC’s Fourth Assessment Report and the IPCC’s recent report on the development of new integrated climate scenarios. He was the principal author for the U.S. EPA’s Technical Support Document on the Benefits of Reducing Greenhouse Gas Emissions for EPA’s Advance Notice of Proposed Rulemaking on Regulating Greenhouse Gas Emissions under the Clean Air Act. He also developed EPA’s social cost of carbon values. He received a Ph.D. in agricultural and resource economics from Cornell University.

Joel B. Smith, vice president with Stratus Consulting, has been analyzing climate change impacts and adaptation issues for over twenty years. He was a coordinating lead author for the synthesis chapter on climate change impacts for the Third Assessment Report of the Intergovernmental Panel on Climate Change and was a lead author for the IPCC’s Fourth Assessment Report. Mr. Smith is on the National Academy of Sciences’ Panel on Adapting to the Impacts of Climate Change. He has provided technical advice, guidance, and training on assessing climate change impacts and adaptation to people around the world and for clients such as the U.S. Environmental Protection Agency, the U.S. Agency for International Development, the U.S. Country Studies Program, the World Bank, the United Nations, a number of states and municipalities in the U.S., the Pew Center on Global Climate Change, the Electric Power Research Institute, the National Commission on Energy Policy, and the Rockefeller Foundation. Mr. Smith worked for the U.S. EPA from 1984 to 1992, where he was the deputy director of the Climate Change Division. He joined Hagler Bailly in 1992 and Stratus Consulting in 1998. Mr. Smith received a Masters in Public Policy from the University of Michigan in 1982 and B.A. (*magna cum laude)* from Williams College in 1979.

Paul Watkiss is an independent researcher with almost twenty years experience of climate change policy support. Mr. Watkiss has particular expertise in the impacts and economic costs of climate change, the costs and benefits of adaptation, and practical use in policy appraisal. He led the UK Defra-commissioned policy study, “The Social Costs of Carbon (SCC) Review: Methodological Approaches for Using SCC Estimates in Policy Assessment” and a study for the European Environment Agency, “Climate Change: The Cost of Inaction and the Cost of Adaptation.” His recent work includes work for the UK Climate Change Committee, advising on potential methods for setting short-term and long-term carbon targets. He is currently the technical director on the DG Research project “ClimateCost,” which is advancing top-down and bottom-up studies of climate change economics (impacts, adaptation and mitigation) across different sectors and regions for Europe, India and China.

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Summaries

May 2010

PEW CENTER ON Global CLIMATE CHANGE

Executive Summary

Based on decades of research by the scientific community, there is now wide recognition that emissions of greenhouse gases are changing our climate and that the future impacts from such changes will largely be harmful. In response, policymakers across the U.S. government are beginning to consider what actions should be taken to limit climate change damages. An important tool used in making such policy choices is cost-benefit analysis (CBA), but this technique has been widely criticized as inadequate as the primary approach to valuing the impacts of climate change.

In March, 2009, the Pew Center on Global Climate Change convened an expert workshop to examine the state of the art, limitations, and future development needs for analyzing the benefits of avoided climate change. Approximately 80 people from academe, federal agencies, and nongovernmental organizations participated. This event was motivated by widespread recognition of two developments: First, policy decisions that result in reduced greenhouse gas emissions are becoming more commonplace across the government. Second, one of the key tools used to analyze such policies, CBA, is challenged by the long-term, global, and uncertain nature of climate change.

Drawing from the environmental economics, impacts and vulnerability, and risk analysis communities, the workshop sought to glean insights on how to better quantify the benefits of reducing greenhouse gas emissions. The main objectives were to inform the development of a set of practical recommendations that decision makers could employ in the near-term and to outline new approaches to improve decision-making tools over time. Based on the outcome of the workshop, the Pew Center responded to the Office of Management and Budget's request for public comments on how to improve the process and principles governing federal regulatory review. In February 2010, the Interagency Working Group on the Social Cost of Carbon issued a report detailing its recommendations for how this metric should be calculated in agency regulatory decisions.

Workshop Themes

Presentations and discussions at the workshop were divided into four thematic sessions.

Session 1: *Perspectives on Government Decision Making for Climate Change*

This session focused on the policy context in which the social cost of carbon (SCC) – an estimate of the benefits of avoided climate change used in CBA – is an appropriate basis for decisions. It examined how other nations (United Kingdom and Australia) had calculated the SCC and what role it had played in setting national policies. It also looked at how, in the past, domestic regulatory agencies had ignored the climate-related benefits from regulatory decisions that had reduced greenhouse gas emissions (e.g., fuel efficiency standards and appliance standards). By incorporating the SCC into these decisions, the agencies could more accurately account for the full costs and benefits of their actions.

Though recognizing that CBA is an imperfect tool, the discussion generally reflected the belief that for decisions with incremental effects on overall emissions, such as individual rulemaking, CBA was appropriate. In contrast, much of the discussion focused on the very different nature of non-incremental decisions (e.g., setting national or global greenhouse gas emissions targets), and that the use of the SCC would be problematic in this context.

Session 2: *Challenges to Quantifying Damages from Climate Change*

This session focused on issues related to quantifying the damages from climate change as a key input into any SCC estimate. The presentations in this session were by scientists who analyze the impacts of climate change. They reported that the complexities and interconnectedness of physical and social systems present many challenges to their ability to produce meaningful quantitative estimates of climate change impacts and their associated costs. They also pointed to the limited case studies available on impacts and the shortcomings of relying on aggregated estimates that necessarily ignore extreme events and variations of social vulnerability through space and time. In addition, presenters highlighted the many difficulties in addressing the uncertainties about the effects of climate change on ecosystems, the susceptibility of ecosystems to thresholds and ecological regime shifts, and the difficulty in monetizing many non-market impacts.

Session 3: *The Role of Uncertainty in Assessing the Benefits of Climate Policy*

This session examined the role of uncertainty in the analysis of climate impacts and focused on risk analysis as an organizing principle for impacts assessment. Information was presented showing that the risks of climate change have increased over the past decade and that delays aimed at reducing uncertainties are not likely to reduce the costs of taking action. This session also explored the use and limitations of integrated assessment models (IAMs) as a key analytical tool for calculating the SCC. It underscored the need for addressing uncertainty in these models through probabilistic analysis of key parameters and the importance of updating and expanding the damage functions they use to reflect more recent impact assessments.

Session 4: *Advances in the Economic Analysis of the Benefits of Climate Policy*

This session offered guidance and new approaches aimed at supporting a broader framework of risk management. The principles and components of an impacts assessment framework were delineated, offering direction on how to make use of available information for decisions with incremental versus non-incremental effects on emissions. Differing, though not wholly incompatible, assessments were made of the usefulness of the discounted utility framework employed by many IAMs and whether this framework can adequately account for uncertainty and potentially catastrophic impacts. The results of recent work with two well-known IAMs were presented. One of them explored risk-adjusted measures of willingness-to-pay with explicit characterizations of the scientific uncertainty surrounding climate sensitivity. Another examined the application of equity weighting in calculating SCCs across a wide range of regions with disparate income levels. Throughout the session practical recommendations for more thorough economic analysis were made, as well as suggestions for improving decision hyphen making tools over time.

Keynote Address: *Beyond Cost-Benefit Analysis*

Professor Gary Yohe offered his perspective on how risk management principles can be applied to climate change using a broader analytical framework that moves beyond CBA alone. Risk management is helpful when there are fundamental uncertainties that cannot be resolved before we have to make decisions. When complete analyses are not possible, Yohe said, identifying levels of risk for specific impacts that decision makers deem intolerable in the local context can help inform decisions regarding both adaptation planning and the level of emissions reductions that would be consistent with identified levels of risk tolerance. Yohe noted that risk profiles lend themselves to a variety of metrics (e.g., number of people at risk, dollar value of property damage, etc.) and can be applied to a variety of spatial scales from global to local, overcoming the problem of excessive aggregation that affects single metrics, such as the SCC. Yohe also pointed to risk profiles that show significant vulnerabilities in the middle of uncertainty distributions (i.e. likely outcomes), not just in the "fat tails," providing sufficient justification for taking action – both adaptation and mitigation – now. By combining multiple metrics, such as improved SCC estimates and a variety of risk profiles, decision makers can gain a more complete understanding of the risks of climate change.

Key Insight

What might be the the most important insight from this workshop was concisely captured by Steven Rose in his background paper:

> *Large uncertainty has bearing on valuation, discounting, and the overall decision approach. For instance, society values reductions in risk, as reflected in different rates of return for high and low risk financial assets. However, deterministic estimates of the value of climate change impacts do not reflect the uncertainty and risk related to climate change, or attitudes towards risk, and therefore ignore the value of reducing risk (i.e. the risk premium). As a result, deterministic estimates underestimate the benefits of emissions reductions, which could be substantial for risks like potential catastrophic events.* (p. 136, this volume)

Economic estimates of the benefits of avoided climate change have so far neglected the value that society places on reducing the risks of severe outcomes with unknown probabilities. Since climate change is rife with risks of this nature, placing a value on risk reduction is imperative in assessing the societal benefits of policies to mitigate climate change.

Expanded Workshop Summary

This summary provides an overview of the 17 expert presentations delivered at the workshop as well as nine accompanying discussion papers presented in this volume. Video of the presentations and the briefing slides used are viewable via the Internet in the online portion of the workshop proceedings. To encourage a free an unfettered exchange of personal insights, discussions during the workshop were not recorded and were off the record.

Summary of Sessions

Session 1: *Perspectives on Government Decision Making for Climate Change.* This session sets the stage for the workshop by outlining the types of decisions that governments need to make regarding the mitigation of climate change and explores lessons that might be learned from the efforts of governments that have been early actors in this arena.

Key insights from Session 1

- Incorporating climate-related benefits into rulemaking increases overall societal benefits from energy and environment regulatory decisions.
- Existing U.S. laws offer many opportunities to produce incremental reductions of greenhouse gas emissions by including climate-related benefits in cost-benefit analyses of regulatory decisions.
- Non-incremental climate change mitigation goals are economically distinct from individual, small regulatory decisions and should be analyzed differently.
- Considerations beyond the quantified climate-related benefits, including non-market impacts and uncertainty surrounding the probability of intolerable outcomes, have been invoked by some governments to justify for more stringent economy-wide mitigation goals than indicated by the optimal policies that emerge from cost-benefit analyses.

In the first presentation – *Incorporating the benefits of climate protection into federal rulemaking* – Martha Roberts of the Environmental Defense Fund aptly frames the issue at the heart of this workshop:

> ***As we move forward on developing [climate policies], a question we are going to face is, 'Is it worth it?' On regulatory policies, on legislation, there is going to be a range of economic analyses that are developed to answer this question. And the quality of these analyses and their reliance on sound science and sound economics is critical to ensure that we move forward in a thoughtful, prudent way that maximizes societal benefits.***

Roberts points out that federal agencies already make many decisions under existing legislative authorities that can and should be used to reduce greenhouse gas emissions. Even though regulations, such as automobile or appliance efficiency standards, are not specifically intended to address climate change, they have a direct effect on greenhouse gas emissions. By including estimates of climate-related benefits in the cost-benefit analyses used to calculate economically optimal policies, these rulemakings can ensure greater benefit to society from individual regulations by reducing future climate damage in addition to conserving energy and protecting air quality.

Dr. Chris Pyke of CTG Energetics reinforces this notion in his presentation, *A proposal to consider global warming under NEPA*. The National Environmental Policy Act (NEPA) implements a permitting process that regulates major actions of federal government agencies that have the potential to impact the natural environment, such as building new roads, clearing land, or designing projects related to water resources. NEPA offers "***a very large number of federal actions that have opportunities to address emissions; opportunities to deal with vulnerability,***" Pyke says. He recommends a Presidential executive order requiring the Chair of the Council on Environmental Quality to consider greenhouse gas emissions and climate impacts for all federal actions regulated under NEPA. Pyke also offers the California Environmental Quality Act as a viable model for how to use NEPA to regulate greenhouse gas emissions at the federal level.

The government decisions that Roberts and Pyke discuss would have marginal effects on individual regulations or projects affecting small portions of the national economy. Another type of decision that must consider the benefits of avoided climate change is major legislation that would set targets for reducing greenhouse gas emissions for the entire economy.

James Lester of Stratus Consulting shifts the focus to economy-wide decisions in his presentation, *Case studies on government decisions to limit greenhouse gas emissions*. As detailed in the accompanying background paper, Lester and Smith ask whether previous decisions by three governments – California, the UK, and Australia – to reduce greenhouse gas emissions were influenced by economic estimates of the impacts of climate change. In general, they conclude that impacts studies influenced decisions in all three cases, but none of them used quantitative benefits estimates to set optimal emissions reduction targets. The UK and Australia performed quantitative comparisons of costs and benefits of alternative climate stabilization targets, but used them principally to justify politically derived emissions reduction targets. One of the great caveats of cost-benefit analysis is that it mostly omits non-market goods and services and ignores unknown probabilities of intolerable outcomes. Lester says that Australia's Garnaut Climate Change Review handles this problem by concluding ***"that a stronger mitigation of 450 ppm is justified by the insurance values and non-market value benefits. So it's worth paying an additional one percent of GDP as a premium in order to achieve 450 ppm rather than 550 ppm."***

In the last presentation, *Climate economics, policy and the social cost of carbon*, Dr. Paul Watkiss of Paul Watkiss Associates takes a closer look at how the UK has employed CBA and SCC estimates in developing its economy-wide climate mitigation goals. The UK government has been analyzing climate change economics for the past decade and, as Watkiss points out, ***"outside of the U.S., the UK has pretty much the strongest tradition of cost-benefit analysis everywhere in the world."*** The UK therefore provides a study of whether ***"a strong tradition of CBA and economics lead[s] you to strong targets, and [whether there] are there lessons for the U.S."*** Watkiss confirms Lester and Smith's conclusion that the UK adopted mitigation goals that were not quantitatively linked to a formal cost-benefit analysis. After years of experimenting with CBA and SCC estimates, in 2009 the UK moved to a shadow price for carbon to achieve consistency with the politically determined long-term goal of reducing UK greenhouse gas emissions to 20% of 1990 levels by 2050. Like Australia, the UK used CBA to show that the benefits of mitigation could be very large, but their analysis also demonstrated that there was great uncertainty surrounding the benefits. In the face of great uncertainty and an unknown probability of intolerable outcomes, the precautionary principle was applied to set political targets informed by qualitative risk assessments. In the resulting risk-reduction framework, the role of economic analysis is to identify cost effective or affordable policies to achieve the UK's pre-determined climate stabilization goal.

Session 2: *Challenges to Quantifying Damages from Climate Change.* This session examines many of the reasons that governments have found it difficult to apply cost-benefit analysis as a guide to long-term climate stabilization goals.

Key insights from Session 2

- Complexities and interconnectedness of physical and social systems present many challenges to the ability of scientists and economists to produce meaningful quantitative estimates of climate change impacts and their associated costs.
- Variations of social vulnerability through space and time are as important to quantifying impacts as is exposure to climate change. Methods that are insensitive to differences in vulnerability and that average out unacceptable local impacts through excessive aggregation cannot sufficiently inform decision makers of the costs of climate change to society.
- Ecosystems are problematic for developing quantitative estimates of the costs to society of climate change impacts. Uncertainties about the effects of climate change on ecosystems, the high susceptibility of ecosystems to thresholds and ecological regime shifts, and the difficulty in monetizing many non-market impacts, make it difficult to value ecosystems and their goods and services to society.
- The inherent difficulty—or impossibility—of maximizing the economic utility of ecosystems has led the government of British Columbia, Canada, to eschew the cost-benefit approach in favor of a sustainability principle that imbues biodiversity with inherent existence value and presumes that ecosystem goods and services are irreplaceable. This framing insures that ecosystem goods and services are not irreversibly lost due to miscalculation of optimal policies.

In his presentation and the accompanying paper in this volume, Dr. Michael MacCracken of the Climate Institute provides an *Overview of challenges to quantifying impacts.* He opens with the statement that ***"I'm rather pessimistic that we can get a real estimate of all the costs of impacts because of the many complexities."*** Initially he points out that large-scale responses of the climate system to human-induced warming have the potential to generate 70 meters of sea level rise (eventually). Integrated assessment models that estimate the costs and benefits of climate change do not capture the potential for such large-scale changes and therefore are unable to estimate the ultimate benefits of avoided climate change. But even for near-term impacts on coasts, agriculture, forest and fiber products, ecosystem services, water resources, and health, system complexities make estimating benefits very challenging. Spatial and temporal complexity and a wide variety of different types of changes are involved. He suggests that, while most analysts are focused on the direct effects of warming, water-related impacts and ocean acidification could be more important. System interconnectedness, nonlinearities, thresholds, surprises, and irreversibilities will make a full accounting of benefits from any given change very difficult. Moreover, the most significant impacts are likely to arise from rare extreme events, rather than the slow changes in averages that IAMs attempt to model. Consequently, MacCracken says, ***"Any estimate you make will be an underestimate and the question is, 'Do we have any conception of how big an underestimate it will be?'"***

Dr. Kristie Ebi, Executive Director of the IPCC Working Group II Technical Support Unit, examines *Social vulnerability and risk* in her presentation and the accompanying paper in this volume. Her point is that ***"social vulnerability is as important as the climatic exposures"*** in determining the severity of impacts, and therefore the benefits of avoided climate change. While IAMs take the approach of attempting to add up exposures, they are incapable of accounting for variations in vulnerability across space and time. Those variations are obscured in traditional cost-benefit analysis because of the aggregation required to obtain a single estimate of benefits. ***"We have to understand the vulnerability of regions if we're going to be able to start talking about the costs of climate change,"*** Ebi says. To illustrate the uniqueness of the climate change problem, she offers the example of lead exposure regulations. Children exposed to a certain concentration of lead will likely experience negative health consequences. The level of exposure to lead varies, but the vulnerability of children to its effects does not. Climate change is different, "because at the same level of climate exposure, we're going to have very different impacts" depending on the level of vulnerability across regions. Because exposure and vulnerability both vary, Ebi says, it is inevitable that that ***"aggregating damages hides unacceptable risks."*** She offers the economic impact of Hurricane Katrina as an example: While damages from the storm cost the U.S. economy less than one percent of its GDP, they cost the states of Louisiana and Mississippi one-third of their combined economic output. ***"When we [use IAMs], we're not taking these [unacceptable] impacts into account,"*** Ebi says.

In his presentation, *Climate change effects on ecosystems and species*, Dr. Tony Janetos, director of the Joint Global Change Research Center, discusses ecological impacts of climate change in the context of the economic benefits of climate policy. He says that climate change is already impacting water resources, agriculture, forests, and biodiversity, and the effects are expected to grow more severe with time. These impacts will likely affect ecosystem services, such as ***"cleaning water and removing carbon from the atmosphere, but we [cannot yet] project the timing, magnitude, and consequences,"*** Janetos says. Additionally, ecosystems are particularly susceptible to crossing thresholds, as illustrated by the current die off of western forests due to the attack by pine bark beetles and widespread bleaching of coral reefs, both due to rising temperatures. New issues are still emerging, as well, such as the effects of ocean acidification from rising atmospheric CO_2 concentrations on marine ecosystems. **"We do not understand what an ocean looks like where organisms are physiologically unable to actually produce calcium carbonate skeletons,"** Janetos says, ***"but no biologist imagines this is good news."*** Even if we could be certain about future impacts, Janetos says that ***"the primary consequences of changes in ecosystems may in fact be in services and benefits that they provide that are not currently priced in markets, but are nonetheless valuable."*** How, then, can we expect to provide reasonable estimates of the economic benefits of avoided ecosystem impacts? ***"For the most part,"*** Janetos concludes, ***"we do not know the answer."***

In *Valuing ecosystem goods and services*, Dr. Jon O'Riordan of the University of British Columbia offers an alternative approach to applying economic principles to ecosystem sustainability in the face of climate change. A key observation is that the province eschews the cost-benefit approach in favor of a sustainability principle that views ecosystems and their goods and services as both valuable and irreplaceable. This approach is rooted in societal recognition of the existence value of British Columbia's exceptionally high biodiversity, the high degree of economic dependence on ecosystem provisions (e.g., food and fiber), and the great importance of non-market regulatory services (e.g., water cleansing, flood control, and temperature moderation) that ecosystems offer. Indeed, the non-market value of Canada's northern boreal forest was estimated to be ten-times greater than its market value. Since the omission of most non-market impacts is a widely recognized shortcoming of CBA, this finding has striking implications for the cost-benefit approach to assessing the benefits of avoided climate change impacts on ecosystems.[1] By policy, therefore, it is presumed that the cost of replacing lost goods and services could be unacceptably high, if possible at all, and measures to avoid such losses serve as insurance against this risk. The policy significance of this approach for is that government decisions are based on ecosystem indicators rather than the estimated relative costs and benefits of policies. Within this framework, ***"access to the ecosystem should be contained by the carrying capacity of that ecosystem."***

Session 3: *The Role of Uncertainty and Risk in Assessing the Benefits of Climate Policy*. The previous session establishes that, among other problems, uncertainty regarding future outcomes is one of the main impediments to developing quantitative estimates of the impacts of climate change, and thus the benefits of avoided climate change. Session three examines the role of uncertainty in the analysis of climate impacts and develops risk analysis as an organizing principle for impacts assessment.

Key insights from Session 3

- The prospects of reducing uncertainty through future learning do not justify a delay in reducing greenhouse gas emissions: Waiting is at least as likely to make policy more costly as it is to make policy less costly. The prospects for learning about abrupt climate change in time to avert it are dim, so managing this risk requires immediate emissions reductions.
- New information about climate change and social vulnerability acquired over the past decade has led experts to perceive much greater risk from lower levels of global warming than they perceived a decade ago.
- The damage functions in the IAMs used for CBA are largely based on decade-old science and omit many categories of impacts. Hence, these models likely underestimate climate impacts.
- Uncertainty in about 30 input parameters to IAMs result in a tenfold or larger range of uncertainty of estimated SCC. This wide range of uncertainty must be considered carefully in the decision-making process.

Dr. Brian O'Neill of the National Center for Atmospheric Research opened the session with his presentation, *Uncertainty and learning – implications for climate policy*. Over time, new information may change our assessment of uncertainty, making us either more or less confident in our ability to forecast the future. Policymakers commonly ask, ***"Should we wait to learn? Maybe we'd be better off having better information before making decisions,"*** O'Neill says. Learning over time may also affect our ability to forecast and avoid damages. He points to good prospects for learning about climate system behavior ***"over the next several decades,"*** and learning about social development paths ***"over the next decade or two."*** He was less optimistic about an abrupt collapse of the North Atlantic overturning circulation: ***"You probably couldn't anticipate that in time to avoid it."*** Model analyses that include reasonable assumptions about learning indicate that policies should

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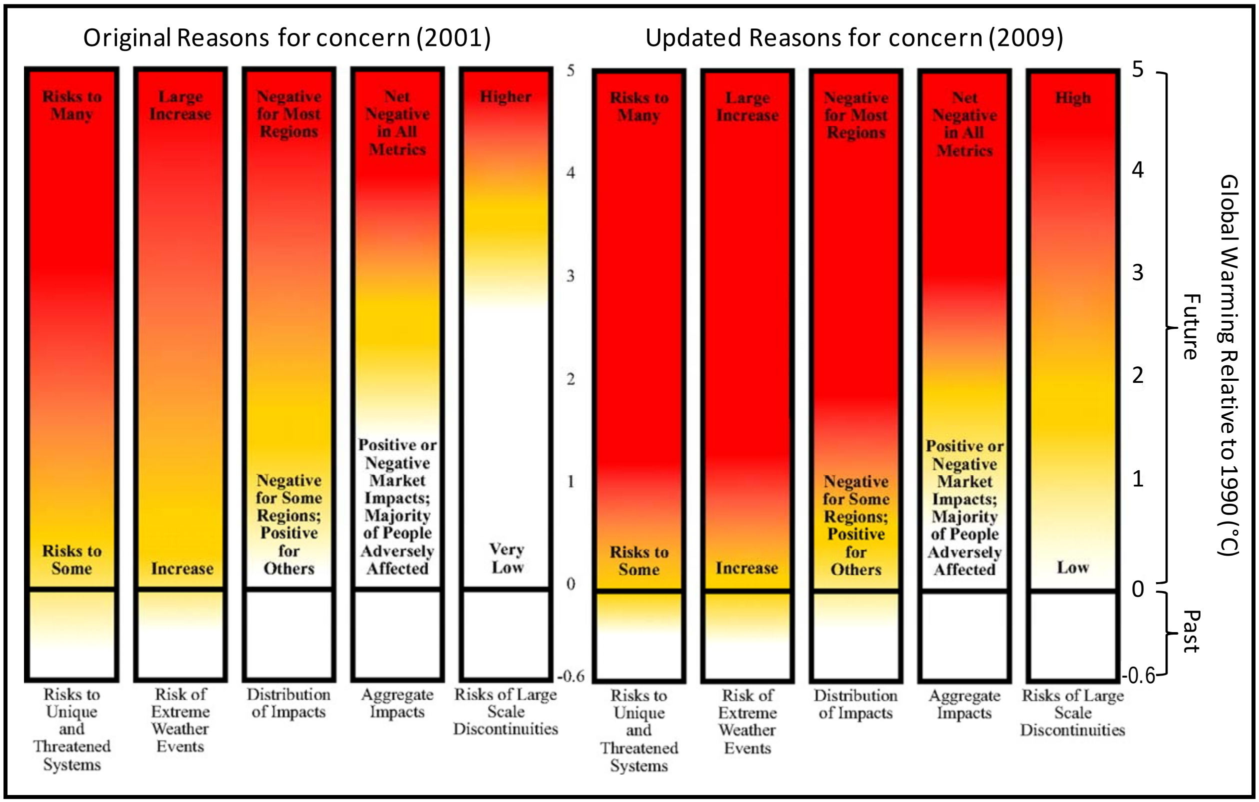
[1] See the papers by Ackerman et al., Mastrandrea, and Yohe in this volume for discussion of non-market impacts.

allow for future course corrections in order to take advantage of new information. On the question of whether or not to begin reducing emissions today, however, O'Neill says, ***"you just never find the case where you add learning to an analysis and it says that we shouldn't do anything now."***

Joel Smith of Stratus Consulting provided an example of learning about climate change risks in his presentation, *Dangerous climate change: an update of the IPCC reasons for concern*. To help policymakers consider the meaning of "dangerous anthropogenic interference with the climate system,"[2] the IPCC's Third Assessment Report, published in 2001, included an analysis of "reasons for concern" (RFCs).[3] The RFCs surveyed the risks of different levels of global warming for five categories of climate impacts: risks to unique and threatened systems (e.g., small-island states, endangered species); risks from extreme climate events; distribution of impacts (e.g., disproportionate effects on the poor or on future generations); aggregate impacts (e.g., total economic losses or number of people at risk); risks from large-scale discontinuities (e.g., collapse of the North Atlantic overturning circulation or rapid global sea level rise). The results of this survey are shown on the left side of the figure above. In 2009, after a decade of learning more about the pace of climate change, vulnerability of societies to extreme events, susceptibility of coral reefs to warming, etc, many of the same experts updated the RFCs (right side of figure above).[4] As a result, Smith says, ***"for all five [RFCs] … the potential for adverse impacts seem[s] to be at lower levels of climate change than we thought in the Third Assessment Report, which is not a good thing."***



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[2] Article 2, United Nations Framework Convention on Climate Change, 1992.

[3] McCarthy J, Canziani O, Leary N, Dokken D, White K , eds (2001) Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge Univ Press, Cambridge, U.K.)

[4] Smith J.B., et al. (2009) Assessing dangerous climate change through an update of the Intergovernmental Panel on Climate Change (IPCC) "reasons for concern." *Proceedings of the National Academy of Sciences* 106:4133-4137.

In his presentation, *Climate impacts in integrated assessment models*, and in the accompanying paper in this volume, Dr. Michael Mastrandrea of Stanford University evaluates economists' ability to model the economic costs of climate change impacts for use in cost-benefit analyses. The integrated assessment models (IAMs) that economists use for this purpose ***"by necessity, incorporate simplified representations of climate impacts."*** Although the IAM developers update the models over time, Mastrandrea says that ***"when most of these [IAMs] were developed … their core impacts estimates are based on the literature from before 2000."*** As a result, the existing literature on the costs of impacts does not yet include the more recent assessment of greater risks from lower levels of warming described by Smith. The damage functions of IAMs typically do not capture key impacts from extreme weather events, ocean acidification, changes in ecosystem services, and increased risk of abrupt sea level rise, Mastrandrea says. ***"Models that do not take these factors into account are likely to underestimate climate damages and recommended emissions reductions."*** While IAMs can be improved by including a broader range of market and non-market impacts and by updating them for advances in scientific understanding, outcomes will remain uncertain and IAMs should represent impacts in a probabilistic manner so that decision makers see how sensitive the estimated cost of damages is to uncertainties in the IAMs.

Dr. Chris Hope from University of Cambridge puts the probabilistic approach into practice in his presentation, *The social cost of CO_2 and the optimal timing of emissions reductions under uncertainty*, and in his accompanying paper in this volume. He has developed one of the prominent IAMs used in CBA for climate policies—the PAGE2002 model. PAGE2002 is the only IAM commonly used in CBA that is designed to produce a probabilistic range of SCC estimates. Using a low discount rate of 1.4 percent and a high emissions scenario (i.e. rapidly growing emissions), PAGE2002 calculates a social cost of CO_2 of $120 per ton, with an uncertainty range of $25 to $320. This wide range is a consequence of ***"about 30 uncertain input parameters that go into the calculation,"*** Hope says. With a constant discount rate, the major influences on the range of SCC are uncertainty surrounding the climate sensitivity (i.e. the rise in global mean temperature that would result from a doubling of the atmospheric CO_2 concentration), the assumed steepness of the model's damage function (i.e. how much more damage occurs as the global temperature rises), the non-market impacts, and the probability and timing of large-scale climate discontinuities. The first and last are scientific uncertainties, while the second and third are economic uncertainties. Brian O'Neill pointed out that the scientific uncertainties are not likely to be resolved for decades. Michael Mastrandrea pointed out that the estimates from IAMs are largely based on the state of the science in about the year 2000. Consequently, Hope says, ***"the new scientific information that's coming in would tend to [suggest] that perhaps the previous estimates that I showed you … are an underestimate of the social cost of carbon dioxide."***

Session 4: *Advances in the Economic Analysis of the Benefits of Climate Policy*. The preceding sessions establish that IAMs likely underestimate climate impacts and suggest the need for a risk-based approach to assessing climate impacts. Session four offers guidance and suggests new approaches that would deploy economic analyses to support a broader framework of risk management.

Key insights from Session 4

- When valuing climate impacts, a different kind of impacts analysis based on risk management is required for policy decisions that concern non-incremental emissions changes leading to large-scale decarbonization of the economy.
- The standard discounted utility framework employed by many IAMs, even when adjusted to account for uncertainty, has not typically been capable of accurately characterizing the precautionary decision to pursue climate stabilization.
- Introducing equity-weighting into marginal damage calculations will produce a different SCC for each region according to its income level and can be used to scale up the external benefit in national cost-benefit analysis.
- Risk-adjusted measures of willingness-to-pay can greatly exceed their deterministic counterparts, underscoring the need for IAMs to account for uncertainty and risk.

In his opening presentation, *Federal decision-making on the uncertain impacts of climate change: working with what you have*, Dr. Steven Rose of the Electric Power Research Institute and formerly of the U.S. EPA offers a practical overview of how to make the most of the information currently in hand. Since human-induced climate change represents a market failure for a global public good—the climate system—it must be addressed through global cooperation: ***"This is not a prisoner's dilemma; this is an assurance game where some minimal level of cooperation is required to actually move the climate needle substantially,"*** Rose says. When a country, especially a large emitter, considers only the domestic impacts of its greenhouse gas emissions in estimating the benefits of avoided climate change, it undermines global cooperation. In addition, when valuing climate impacts, an analytical gap exists between policies with incremental as opposed to non-incremental effects on emissions. Marginal value estimates are acceptable for the appraisal of incremental policies in order to provide some consistency with a country's overall climate objective. These marginal values could be SCC estimates calculated on the basis of appropriate discounting and inclusion of a broader array of impacts. Or, as in the UK, they could be the "shadow price of carbon" associated with some large scale policy choice, such as an emissions stabilization target, that represents a tolerable or acceptable level of risk. Non-incremental decisions aimed at large-scale decarbonization of the economy require a different kind of impacts analysis. Even probabilistic SCC estimates that account for uncertainties are not sufficiently robust for setting an economically optimal emissions pathway. In his paper in this volume, Rose lays out the principles and components of an impacts assessment framework and the risk assessment tools that support it.

Prof. Richard Howarth of Dartmouth College focuses his presentation, *The need for a fresh approach to climate change economics*, on the issue of discounting, particularly how discounting and the characterization of rational decision making under uncertainty interact. He challenges the underlying assumption employed by deterministic IAMs that decision makers maximize a standard two-parameter social welfare function in a discounted utility framework with perfect foresight.

Howarth notes that financial economists do not use this model to study asset markets and savings and investment behavior, because it assumes away the uncertainty and risk that are key explanatory factors in determining actual returns on investment. However, he underscores that even the generalized Ramsey framework that incorporates risk and uncertainty cannot be validated by historical data from financial markets. Based on the recent work of Weitzman, Howarth says one way of resolving this "equity premium puzzle" is to assume that risk aversion drives investors to attach high subjective weight to low probability "disasters." This is rational because of the paucity of observational data and the inability to form reliable statistical representations of risk. Discounting considerations then become immaterial in formulating a rational policy. "***Metaphorically, the precautionary decision to pursue climate stabilization is like buying an insurance policy***," Howarth says. Precautionary actions reduce major perceived risks to future social welfare, moving society from a relatively risky (no-policy) consumption and utility stream to one that might have a lower expected value but also a reduced risk of climate catastrophe and the very large losses that would ensue. In the accompanying paper by Ackerman et al., Howarth and his colleagues develop the case for a decision-making framework in which economy-wide mitigation goals are derived from scientific assessments of climate impacts and economic tools are used to identify cost effective policies to achieve those goals.

In his presentation, *National decision making on climate change and international equity weights*, David Anthoff of the Economic and Social Research Institute examines the benefits of mitigation from a global versus national point of view. In his illustrative example using the FUND model, a one ton reduction of carbon emissions anywhere in the world produces a global benefit (SCC) of $21/tC. Of this global benefit, only 6% or $1.3 is realized within U.S. borders and $19.7 accrues to the rest of the world, illustrating the unusual nature of the climate issue. However, Anthoff notes that various branches of the economics literature have questioned the appropriateness of simply adding up each region's willingness-to-pay for mitigation to determine a global SCC value. This objection follows from the standard assumption of declining marginal utility of consumption, which implies that the same absolute consumption decline will cause greater welfare loss in a poor country than in a rich one. IAMs already capture the effect of wealth differences between generations and Anthoff sees no obvious reason why they should not capture the same differences across countries within a generation. The implication is that when a wealthy country like the U.S. ascribes a value to climate damages for the purposes of national cost-benefit policy appraisals, not only should the external, non-U.S. benefit be included, but it could be computed in welfare-equivalent terms by scaling up the portion of the benefit that accrues to poor countries. In the illustrative example, the $19.70 international benefit would then become $172.30, adjusting for the distribution of income in countries outside the U.S. Says Anthoff, ***"This is not how cost-benefit analysis is normally done, but in normal circumstances you're not dealing with such large differences in income distribution as you do with climate change."***

Dr. Stephen Newbold of the U.S. EPA takes a novel approach to incorporating uncertainty into decision making. His presentation, *Climate change policy benefits and uncertainty*, derived from his coauthored paper in this volume, considers the economic benefits of greenhouse gas emissions reductions within an expected utility framework that accounts for scientific uncertainty surrounding the climate sensitivity—i.e. the amount of warming that would result from a doubling of the atmospheric CO_2 concentration. Since the climate sensitivity is a key driver of damage estimates in IAMs, a wide range of uncertainty around a central estimate could introduce a socially unacceptable level of risk of severe outcomes compared to a narrow range. Given that the scientific literature documents a broad range of uncertainty, Newbold asks, what is society's "willingness to pay" (WTP) for emissions reductions? Compared to a deterministic model that ignores uncertainty—i.e. considers only a "best estimate" of the climate sensitivity—Newbold's analysis using the DICE model finds ***"a risk-adjusted WTP for the optimal emissions path … that's nearly five times the deterministic estimate."*** Failing to consider uncertainty therefore underestimates how much society values risk reduction. In contrast to Ackerman et al. in this volume, Newbold is optimistic that fuller exploitation of the expected utility framework can overcome some of the key limitations of CBA. He says that his approach is analogous to determining the value of an insurance policy against the worst-case outcomes and demonstrates that the expected utility framework can account for uncertain but potentially catastrophic events, while still weighing the costs and benefits of incrementally more or less stringent policies. He argues that an "adaptive management" framework that includes learning and iterative decision-making can provide an integrated framework for optimizing both our policy instruments and our research expenditures over time.

Keynote Address: *The long view: developing a new decision-making framework based on the IPCC's "iterative risk-management" paradigm*. Given the general consensus that SCC and its application in CBA is insufficient on its own to guide non-incremental decisions about mitigation climate change, Prof. Gary Yohe offers his perspective on moving beyond CBA.

In his keynote presentation and background paper included in this volume, Prof. Yohe explores how to operationalize an iterative risk management paradigm for climate change decision making. He argues that risk management is necessary when there are fundamental uncertainties that cannot be resolved in a timely fashion – our understanding of climate sensitivity, for example – before we have to make decisions. He reviews how estimates of economic damages from climate change have failed to address many possible non-incremental climate impacts due to numerous uncertainties and the limitations of current methods. According to Yohe, ***"It is folly to do nothing for 10 or 15 years in the hope that science will resolve some of these uncertainties."*** He is not sure that even then could we economically categorize these kinds of impacts. When complete analyses are not possible, Yohe suggests that identifying critical thresholds – points beyond which the impacts of climate change become intolerable – can be productive and can simplify the application of a risk management approach. He provides a real world example of the 100-year coastal flooding anomaly for New York City. Running a simplified model using probabilistic emissions scenarios and applying a wide range of climate sensitivities, he constructs risk profiles of the recurrence interval in years of the potentially devastating storm. These risk profiles form one component of a broader risk matrix depicting New York City's vulnerability to a host of extreme weather events, and can be used to prioritize protective measures that need to be implemented early and those that can be deferred. Yohe closes by noting that risk profiles lend themselves to a variety of other metrics (number of people at risk, dollar value of property damage, etc.). Importantly, they can also show that some significant vulnerabilities appear in the middle of distributions, not just in the "fat tails," providing sufficient justification for taking action – both adaptation and mitigation – now.

Glossary of Terms and Concepts

Costs and ***benefits*** take on broader meanings in the context of government decision making. *Social costs* refer to the value of resources that are used to implement a policy and as a result cannot be employed in some other activity. *Social benefits* are the favorable effects that a policy has on society as a whole.

Cost-benefit analysis (CBA) is a quantitative comparison of the social costs and benefits of implementing a policy. A policy is not economically justified at a societal level if the estimated net benefits (benefits minus costs) are negative. Assuming that both social costs and benefits can be estimated accurately, and that there is a choice among alternative policies, the economically *optimal policy* is the one that maximizes estimated net benefits.

Social cost of carbon or CO_2 (SCC) is the net present value of global climate-related damages over one or two centuries of one additional ton of greenhouse gases emitted to the atmosphere at a particular point in time. The SCC is therefore an estimate of the economic benefits – ideally, society's willingness to pay – of avoiding one metric ton of carbon being emitted to the atmosphere. It is typically expressed in dollars per metric ton of carbon and it increases as the concentration of atmospheric CO_2 rises. SCC estimates can be used to represent the benefits of avoided CO_2 emissions in CBA of mitigation policies.

Integrated assessment models (IAMs) are numerical models that incorporate simplified representations of climate and socioeconomic systems, and interactions between them, to estimate the costs and benefits of climate policies. When used in CBA, IAMs seek to calculate optimal policies (e.g., the optimal amount and timing of greenhouse gas emissions reductions). Whether IAMs are able to produce accurate assessments, particularly for the SCC (benefits), is discussed at length in these proceedings.

Shadow price of carbon (SPC) refers to the methodology used by the UK government to value carbon in national cost-benefit policy appraisals. The SPC was based on the value of the SCC from the 2006 Stern Review that was consistent with an atmospheric concentration scenario of 550 ppm CO2e, and adjusted upward for technology and policy considerations.

Incremental and ***non-incremental*** (or *marginal* and *non-marginal*) describe policy changes that would achieve "small" and "large" reductions in greenhouse gas emissions, respectively. In practice, incremental emissions reductions will be achieved under existing laws as the benefits of avoided climate change are already being incorporated into CBAs that guide routine regulatory decisions, such as new appliance efficiency standards. Non-incremental reductions would achieve large-scale decarbonization of the national economy. Mitigation on this scale would likely only be achievable through new legislation aimed specifically at achieving long-term stabilization of the climate system, using an economy-wide carbon pricing mechanism as its core component.

Background Papers for Session 1:

Perspectives on Government Decision Making for Climate Change

WORKSHOP PROCEEDINGS

Assessing the Benefits of Avoided Climate Change: Cost-Benefit Analysis and Beyond

The Economics of Climate Change Impacts: A Case Study on the Motivation for Government Decisions to Limit Greenhouse Gas Emissions

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Stratus Consulting, Inc.

May 2010

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The complete workshop proceedings, including video of 17 expert presentations, this summary report, and individual off-prints of expert papers are available free of charge from the Pew Center on Global Climate Change at http://www.pewclimate.org/events/2009/benefitsworkshop.

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The Economics of Climate Change Impacts: A Case Study on the Motivation for Government Decisions to Limit Greenhouse Gas Emissions

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Abstract

In the years since the adoption of the Kyoto Protocol, many developed countries and regional and state governments have begun taking more ambitious action on climate change by setting their own emission reduction goals and enacting a variety of greenhouse gas (GHG) emissions reduction policies. While many of these decisions have been based on a precautionary outlook to avoid dangerous climate change, policymakers are also evaluating the costs and benefits of emissions reductions at the global or domestic levels, and in some cases both.

This report reviews three case studies representing different government decisions: the United Kingdom, Australia, and the State of California. These governments used economics as motivation for the development of mitigation policies and have been among the leaders in adopting ambitious goals for GHG emissions reductions. They have also undertaken an extensive analysis of potential impacts and in some cases, have attempted to estimate some of the resulting global and local economic damages from climate change. While it appears that none of the governments undertook a formal benefit-cost analysis using the future benefits of avoided climate change to set its GHG reduction targets, the estimation of the benefits of avoided impacts may have played a role in justifying climate policies.

Introduction

Many governments at the national and sub-national levels have adopted greenhouse gas (GHG) emissions reductions targets. Information on climate change impacts has informed government level discussions on mitigation and has quite likely contributed to the adoption of a range of mitigation measures. For example, European Union (EU) countries such as The Netherlands, and U.S. states such as Washington and Massachusetts, have adopted mitigation measures with the aid of impact assessments. The motivation for adopting such targets has been to avoid the adverse impacts of climate change. For example, the EU has adopted a goal of limiting the increase in global mean temperature to 2°C above pre-industrial levels (EC, 2007). Even the U.S. Supreme Court has acknowledged that future impacts must be taken into account in policy decisions. They ruled in Massachusetts v. the U.S. Environmental Protection Agency (EPA) that EPA's refusal to regulate carbon dioxide (CO_2) has led to "actual" and "imminent" harm, mainly in the form of rising sea levels along the state's coast. The ruling also noted "the harms associated with climate change are serious and well recognized" (Pew, 2007).

As other governments such as the United States address national goals for GHG emissions, an important matter is whether it is necessary to quantify, and more specifically monetize, the impacts (oftentimes referred to as "damages") from climate change to justify emissions reductions. Such analysis can be used to compare monetary benefits of emissions reductions (i.e. value of avoided impacts) with the costs of emissions controls. As a result of the Supreme Court ruling, in June 2008, EPA's "Technical Support Document on Benefits of Reducing GHG Emissions" outlined key concepts and strategies for estimating the social cost of carbon values (Roberts and Spencer, 2008).

This report explores the economic motivating factors behind select governments actions. In particular, it will address whether estimates of total damages from climate change (and benefits from avoiding climate change) were developed and whether those estimates were used to or informed setting of GHG reduction goals or targets. This report reviews three case studies representing different government decisions: the United Kingdom (UK), Australia, and the State of California. It will explore how these governments used economics as motivation for the development of mitigation policies.

Climate agreements and policies have often not utilized economic analysis. The United Nations Framework Convention on Climate Change (UNFCCC) has been the centerpiece of global efforts to combat climate change. In 1997, the UNFCCC Conference of Parties agreed on the Kyoto Protocol. Under this protocol, industrialized countries agreed to reduce their collective GHG emissions by 5.2 percent compared to year 1990 levels by 2008 to 2012 (UNFCCC, 1997). Rather than formally measuring the costs and benefits of the targeted reduction, UNFCCC policymakers decided on what is known as a precautionary approach. The "precautionary principle" states that where there are threats of serious or irreversible damage, the lack of full scientific certainty should not be used as a reason for postponing such measures, taking into account that policies and measures to deal with climate change should be cost-effective to ensure global benefits at the lowest possible cost (UNFCCC, 1992).

Although it did not recommend a level at which GHGs should be stabilized, the Intergovernmental Panel on Climate Change (IPCC) found that substantial reductions, well below those required under the Kyoto Protocol, would be required to avoid many adverse impacts of climate change. For example, the lowest stabilization level analyzed, a carbon dioxide equivalent (CO_2e) concentration level of 350 to 400 parts per million (ppm), would result in global temperatures 2 to 2.4°C above pre-industrial levels (the EU target), and would necessitate a 50 to 85 percent reduction in GHG emissions below 2000 levels by 2050 (IPCC, 2007a). The IPCC estimated that such reductions could be achieved at an annual cost of around 0.1 percent of gross domestic product (GDP). It did not estimate the value of avoided climate change impacts.

In the years since the adoption of the Kyoto Protocol, many developed countries and even regional and state governments have begun taking more ambitious action on climate change by setting their own goals above and beyond the Kyoto Protocol and enacting a variety of GHG emissions reduction policies. Indeed, many nations and sub-national governments have adopted the 2°C target. While many of these decisions have been based on a precautionary outlook to avoid dangerous climate change, policymakers are also evaluating the costs and benefits of emissions reductions at the global or domestic levels, and in some cases both. This report analyzes the motivations for such action by a few governments: the UK, Australia, and California. These governments have been among the leaders in adopting ambitious goals for GHG emissions reductions. They have also undertaken an extensive analysis of potential impacts and in some cases, have attempted to estimate some of the resulting global and local economic damages from climate change. These impacts include among others; increased droughts, a rise in sea levels, and an increase in heat-related illness and disease. The economic damages include changes in energy demand, reduced agriculture output, and increased infrastructure damage and health care costs, among many other economic costs. This report examines the analyses done and attempts to assess whether and to what degree economic analysis of climate change impacts influenced the selection of mitigation targets.

Climate Change Economics: Measuring the Costs and Benefits

This section briefly explains some concepts that some readers may find useful in understanding this report. A key component of estimating future costs of climate change are impact assessments. Impact assessments are detailed estimations of the consequences of future climate change and sea level rise on ecosystems, water resources, agriculture and food security, human health, coastal, and other sectors. Outputs from models of the estimated climate impacts can be entered into socioeconomic models (integrated assessment models[1]) which link climate, impacts and economic costs into an integrated system to estimate the economic effects of these impacts (Roberts and Spencer, 2008). National studies can also utilize impact studies combined with general circulation models (GCM) to estimate regional or national market impacts. The results of these models can help analysts estimate economic losses. Using some of these concepts and tools, governments such as the UK, Australia, and California have helped establish that climate mitigation is vital to the long-term health of its economies.

Estimations of economic losses from climate change typically include more than financial impacts. Climate change losses include financial (market) impacts such as increases in crop prices, costs of building sea walls, and the value of inundated coastal lands. But, a number assessments of climate change losses (e.g., Nordhaus and Boyer, 2000; Tol, 2002) include estimates of so-called "non-market impacts" such as loss of ecosystems and non-market values of human life. Some of these assessment also include insurance values that describe how much we are willing to pay to avoid a small probability of a highly damaging or possibly catastrophic outcome (Garnaut, 2008). Non-market impacts affect ecosystems or human welfare, but are not easily expressed in monetary terms (IPCC, 2007). These non-market impacts are typically combined with financial or market impacts to estimate total economic impacts. The total values are often compared to GDP, even though a significant portion of the total damages would not be seen in typical GDP accounts.

Besides estimating the value of total damages, another tool for expressing climate change damages that has been widely employed is estimating the damages from emissions of ton of carbon. The "right" price of carbon is often called the "social cost of carbon" (SCC), which can be interpreted as a measure of the marginal damages from emission of an additional ton of carbon. Conversely, it can be thought of as the benefit of avoiding emission of a marginal ton of carbon. In other words, the SCC signals what society should be willing to pay now in order to avoid future damages caused by incremental CO_2e emissions (DEFRA, 2007). One of the many complex issues that face decision-makers is that the costs of mitigation come much earlier than the benefits of avoided climate change. Economists consider a dollar in future years to be less than a dollar today, because a dollar today can be invested and grow over time. Future damages from climate change are reduced (in present value) the further into the future they occur (DEFRA, 2007).[2]

Another important issue is that the impacts of climate change are unlikely to be evenly distributed, either between regions or between income groups. A loss of income among poor people or in poor countries will be more harmful than the same loss of income among wealthier individuals or countries (Garnaut, 2008). To address this, economists use an approach called equity weighting, which gives more weight to impacts on poorer countries and individuals. The application of equity weighting can dramatically affect SCC values.

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[1] See the paper by Mastrandrea in this volume for an overview.

[2] Note that there is substantial controversy over what discount rates are appropriate to use for inter- generational consequences of greenhouse gas emissions (Newell & Pizer, 2003).

Applying appropriate discount rates and equity weighting techniques is a complex and highly debated topic. Different choices of these rates can result in widely varying estimates of SCC (Watkiss and Downing, 2008).

The following case studies examine how some prominent governments have attempted to measure the costs and benefits of mitigating climate change. While these governments did not perform a formal environmental benefit-cost analysis, they did try to estimate the costs of climate impacts, and could use these estimates as motivation or justification to pass climate legislation or announce emissions reduction targets.

Case Study 1: United Kingdom

Overview

The UK has for the last decade been a global leader in developing an understanding of the costs and risks of climate change by sponsoring leading research into both mitigation and adaptation. Examples include the implementation of an official Social Cost of Carbon in 2002 (GES, 2002), the recent government-commissioned Stern Review on the Economics of Climate Change (Stern, 2006), and the research of the UK Climate Impacts Programme (which started in 1997), which brings together the scientific evidence for climate change impacts and adaptation in the UK. The UK has taken several steps to measure benefits and costs that could justify its stated climate targets.

The Department for Environment, Food and Rural Affairs (DEFRA) published its first national assessment of the possible impacts of climate change on the UK, the Climate Change Impacts Review Group (CCIRG) report in 1991, followed by a second CCIRG report in 1996 (CCRIG, 1996). The UK signed the Kyoto Protocol in the spring of 1998, with formal ratification in 2002. The UK's target of GHG emissions reductions under the agreement was a 12.5 percent reduction by 2008-2012 compared to 1990 levels (DEFRA, 2007). This commitment led to the development of the UK's first national Climate Change Programme in November 2000. The program identified both the risks associated with climate change, and also a range of policy measures and initiatives. These included innovative new policy measures, a climate change levy (a tax on electricity), c**limate change agreements with industry,** and a UK emissions trading scheme. Climate change also played a major role in shaping the influential 2003 Energy White Paper, which proposed a 60 percent reduction of CO_2 emissions relative to 1990 levels by 2050 (UK, 2003).

In November 2008, the UK passed the Climate Change Act 2008, which created the world's first long-term, legally binding framework to reduce GHG emissions to at least 80 percent by 2050 (DEFRA, 2008) and at least a 26 percent reduction in CO_2 by 2020 – with the 2020 target to be updated following advice from the Climate Change Committee (CCC), an independent body set up as part of the Act. The CCC has recommended two sets of carbon budgets: the **Intended budget,** which will apply following a new global deal on climate change; and the **Interim budget**, which will apply before a global deal is reached. As

proposed by the CCC, the Intended budget would require an emissions reduction of 42 percent in 2020 relative to 1990, and the **Interim budget** would require an emissions reduction of 34 percent in 2020 relative to 1990 (CCC, 2008a). These targets link to the recently adopted European Commission 2020 target of at least a 20 percent reduction in GHG emissions by 2020 on 1990 levels – rising to 30 percent if there is an international agreement, and the UK's potential split of this target under the burden sharing agreement. The UK Government is currently reviewing the CCC advice, and announce proposals for the level of the first three carbon budgets (2008-12, 2013-17 and 2018-22) in the Spring of 2009.

Studies of Climate Change Impacts and Economic Costs

A number of studies of climate change impacts have been undertaken to help understand how the UK will be affected by climate change. A qualitative impact study has also been completed for each region in the UK, and a number of quantitative and economic sector-specific studies have been undertaken as well. There has been one cross-sectoral analysis of the economic impacts in the UK (Metroeconomica, 2006). The UK Climate Impacts Programme produced guidelines that describe a methodology for calculating the costs of climate impacts and explains how to compare these to the costs of adaptation measures (UKCIP, 2004).

The Stern review is the one of the more comprehensive reviews on the economic costs of climate change. Although the review took a global outlook, it has been very influential in UK policy since its publication in 2006. The review made use of many impact studies and estimates that the cost of inaction on climate change significantly outweighs the projected cost of coordinated global action, contingent on the specific assumptions it made. The review predicts that the value of the damages from unmitigated climate change could be significantly more (up to 5 to 20 percent of GDP) than the global cost of action to stabilize atmospheric concentrations of GHGs at 550 ppm CO_2e (Stern, 2006).

The review considered the economic costs of the impacts of climate change for business-as-usual growth and the costs and benefits of action to reduce the emissions of GHGs, but it does not look at the benefits (in economic) terms of mitigation. It is important to note that there are still residual costs as a result of mitigation, (Stern, 2006):

- It considered physical impacts of climate change on the economy, human life, and the environment, and examines the resource costs of different technologies and strategies to reduce GHG emissions
- It included integrated assessment models that estimate the economic impacts of climate change, and macro-economic models that represent the costs and effects of the transition to low-carbon energy systems for the economy as a whole
- The review used comparisons of the current level and future trajectories of SCC with estimated marginal abatement cost.

One controversial aspect of the Stern Report was its use of a low discount rate. Many experts argue that the review adopted a global rather than a national perspective, with substantial aversion to risk, and consideration of intertemporal and geographical equity (Watkiss and Downing, 2008). Therefore, a lower discount rate and equity weighting was used than most UK estimates, resulting in a relatively high estimate of damages. The use of such a low discount rate has been criticized by a number of economists (e.g., Yohe, 2006; Nordhaus, 2007).

Using an integrated assessment model, Stern estimated the cost of business-as-usual climate change to equate to an average reduction in global per-capita consumption of 5 percent at a minimum. Stern estimated economic and non-economic (non-market) costs, and also discontinuities into its analysis. It estimated that the potential scale of the climate response could increase the cost of climate change from 5 to 7 percent, and non-market costs could increases the total cost of unmitigated climate change from 5 to 11 percent (Stern, 2006). The review also describes how many important effects are omitted from the analysis because of uncertainty. Cost estimates would increase if the analysis incorporated effects such as distributional impacts, dynamic feedbacks, and social contingent impacts.

The Stern review also influenced the Social Cost of Carbon used in UK government. In 2002, the UK Government (GES, 2002) recommended an illustrative marginal global SCC estimate, based on the economic literature at that time, for use in policy appraisal across Government (an illustrative marginal global SCC estimate of £70[3]/tonne of carbon (tC), within a range of £35 to £140/tC, rising at £1/tC per year from the year 2000). These SCC values have been used widely in regulatory impact appraisal and in the consideration of environmental taxes and charges, though it was not used to set medium or long-term greenhouse gas emission targets. The results of the Stern review were used to update this value. . The Stern review arrived at a value for the SCC (at £60/tCO_2 or £218/tC) that was several times the existing UK SCC and the wider literature, even though the Stern analysis uses many of the same models and damage functions.

However, a further modification was made to the Stern SCC value before implementation. The UK Government (DEFRA) modified the Stern estimate into an official shadow price of carbon (SPC) by using a Stern SCC estimate that assumes the recommended Stern emissions stabilization trajectory, based on a 550 ppm CO_2e future (DEFRA, 2007). This reduces the SCC value to £30/tCO_2 for a current emission[4]. This differs from a traditional shadow price, which usually is determined by the intersection of marginal damages and marginal abatement costs (FOE, 2008). While the SCC is purely a measure of the damage caused by carbon and the manner in which this is valued, the SPC is regarded by DEFRA as a more versatile concept which can be adjusted over time to take into account policy development and technological advancement (DEFRA, 2007). Government ministers must

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[3] £70 = $100.23. 1 GBP = 1.43 (2-26-09) http://finance.yahoo.com/q?s=GBPUSD=X.

[4] The Stern SCC value for a 550ppm CO2e target (£30/tCO_2) was updated for a 2007 emission, expressed in 2007 prices, to £25/tCO_2e.

factor a carbon price when making all policy and investment decisions covering transport, construction, housing, planning, and energy (Wintour, 2007). The UK Treasury's "Green Book" guidance adopts the SPC as the basis for incorporating carbon emissions in project level benefit-cost analysis and regulatory impact assessments (PWA, 2008).

Analysis of Mitigation Policies

"The Impact Assessment of the Climate Change Bill," published in 2007, contains a high-level discussion of the costs and benefits of UK action to mitigate climate change to a degree consistent with the government's established medium and long-term objectives, along with an analysis of the key drivers and uncertainties surrounding these assessments (UK, 2007). The assessment draws on a range of different modeling results applicable to both the UK economy and draws on analogous mitigation cost studies in other developed countries. The impact assessment includes research undertaken as part of the Stern review, together with analysis conducted for the 2007 Energy White Paper (UK, 2007).

The recently passed Climate Change Act requires that emissions be reduced by at least 80 percent by 2050, compared to 1990 levels (DEFRA, 2008). In meeting these requirements, the government focused on GDP impacts of the carbon budgets, which was estimated using three alternative models (resource cost, macroeconometric, and general equilibrium). The government used the MARKAL-Macro model, which focuses on long-run mitigation costs of meeting the 2050 target, as well as a study conducted by Oxford Economics to explore the potential short-run adjustment costs of meeting a 2020 target (DEFRA, 2007).

After reviewing the economic impacts of climate change, the Stern review analyzed the costs of mitigation options. The review's analysis found that the costs for stabilization at 500-550 ppm CO_2e were centered on 1 percent of GDP by 2050, with a range of plus or minus 3 percent around the central estimate. To put into context, global GDP is projected to be around $100 trillion by 2050, thus annual costs would approach $1 trillion (Stern, 2006). The range reflects a number of factors, including the pace of technological innovation and the efficiency with which policy is applied across the globe (Stern, 2006). The estimates do not take co-benefits into account, for example, in terms of reduced ill health and environmental damage from reduced air pollution levels and increased energy security. The review estimated that meeting the stabilization targets would reduce the percentage loss of climate change impacts to 0.6 percent of global GDP. The Stern report uses its estimates of avoided damages resulting from climate change mitigation and weighs them against the costs, and concludes that the costs of inaction would likely be much more significant in terms of damage to the world economy (Stern, 2006).

The UK's Decision Process

A review of UK policies over the past decade have found several occasions where the government used a SCC in regulatory impact appraisal and in the consideration of environmental taxes and charges. The UK's most recent white paper analysis of the Climate

Change Act goals considered the SCC in the analysis of the necessary short-term steps toward an 80 percent reduction, but the value was not used explicitly in the benefit-cost analysis of the long-term goal (PWA, 2008). Stern's economic analysis is often credited as a key motivation behind such an ambitious mitigation target, but in fact, an earlier 60 percent long-term target (consistent with a 2 degrees target) preceded the Stern review by some years, and there were already moves to consider updating the target, due changes in the science (i.e. that a 60 percent reduction would not achieve the previous 2 degrees ambition level; IPCC, 2007c). While it compares the costs of inaction against the cost of taking action and does not include specific estimates of avoided damages, the real justification for action is focused on a multi-attribute analysis that shows stabilization levels and probability ranges for temperature increases. Yet, as stated by Ed Miliband, Secretary of State at the Department of Energy and Climate Change, "The reductions required can be achieved at a very low cost to our economy: the cost of not achieving the reductions, at national and global level, will be far greater" (CCC, 2008b).

Case Study 2: Australia

Overview

The IPCC report, "Climate Change 2007: Impacts, Adaptation, and Vulnerability" (IPCC, 2007b), finds that Australia is one of the most vulnerable of all industrialized countries to the impacts of climate change. This reflects Australia's already variable and semi-arid climate, poor soils, vulnerable ecosystems, and a high proportion of the population living in coastal areas. A comprehensive economic analysis of the impacts of climate change was commissioned by the government, known as the Garnaut Climate Change Review (Garnaut, 2008). The review focused on economic impacts on Australia, but also included global impacts, compared to the Stern review, which took a solely global outlook. The review was highly influential in the Australian government's most recent climate reduction target.

While the Australian government has not been as active on climate issues as the UK, it has recognized the importance of impacts and adaptation with the establishment in 2004 of a National Climate Change Adaptation Program. This program prepares all areas of government, vulnerable industries, communities, and ecosystems to manage the consequences of climate change. The Adaptation Program is closely linked with the Department of Climate Change, established in 2007, which improves the scientific understanding of the causes, nature, timing, and consequences of climate change to better inform industry and government decision-makers. Based on the Garnaut review, Treasury modeling, and previous climate impacts research, the Australian government has endorsed a carbon emissions reduction target of 15 percent by 2020, following the introduction of a carbon trading scheme in 2010. A more ambitious 25 percent reduction target would be kept open as a possibility if the international community agrees to ambitious targets at a United Nations Summit in Copenhagen at the end of 2009 (Reuters, 2008).

Studies of Climate Change Impacts and Economic Costs

In an attempt to measure the costs of climate change, Australia produced "*Climate Change: An Australian Guide to the Science and Potential Impacts"* in 2003 (Australia Office of Climate Change, 2003). The analysis found that climate change is projected to increase the severity and frequency of many natural disasters, such as bushfires, cyclones, hailstorms, and floods. Insured losses from these events are estimated to total billions of dollars (Australia Office of Climate Change, 2003). An update to the analysis also identified the following potential effects and costs of climate change to Australia's economy (Australia Office of Climate Change, 2008):

- The drought that began in 2002 was estimated to cut growth in the country's GDP by 0.7 percent in 2007. Restrictions on water use in Australian cities resulting from the current drought have cost around $900 million a year and affected over 80 percent of Australia's households.
- The frequency of drought may increase by up to 20 percent over most of Australia by 2030, and up to 40 percent in southeast Australia and 80 percent in southwest Australia by 2070.
- Water flows into the Murray-Darling Basin, already stressed, are estimated to decline by 15 percent if the temperature warms by 1°C. Reductions in flows of around 50 percent are possible by the end of the century. Irrigated agriculture in the Murray-Darling Basin could decline by up to 92 percent.
- If the temperature rises by 2°C, national livestock carrying capacity is projected to decrease by 40 percent.
- Changes in temperatures and rainfall are projected to increase road maintenance costs by 31 percent by 2100.

In 2004, Australia released "Economic Issues Relevant to Costing Climate Change Impacts" (Australian Greenhouse Office, 2004), which identifies sectors of the Australian economy that are particularly vulnerable to climate change, and estimates the costs of climate change for some of these sectors. The sectors reviewed include agriculture, biodiversity (which includes national reserves, species diversity, and ecosystems), coasts (which includes fisheries, marine life, the Great Barrier Reef, and coastal infrastructure), forests (which includes natural and plantation forests), settlements (which includes infrastructure, local government, planning, human health, transport, energy, and emergency services), and water (which includes drought, water quality, and water supplies) (Australian Greenhouse Office, 2004).

Building upon previous impacts studies, the Garnaut Climate Change Review was an independent study commissioned by Australia's Commonwealth, and state and territory governments. The review examined the impacts of climate change on the Australian economy, and recommended medium- to long-term policies and policy frameworks to improve the prospects for economic growth. To test the case for action, the review compared a scenario of no mitigation (or business-as-usual) and a scenario of a 550 ppm future, and compared the costs of mitigation of climate change with the benefits of avoiding climate change (Garnaut, 2008). The report estimated that the global gross national product (GNP) would fall by around 8 percent by 2100, with losses in developing countries likely to be higher than the global average. Among the impacts for Australia that the review estimated were that unmitigated climate change causes real wages to be around 12 percent lower than they would otherwise have been. The largest impacts were found in agriculture and mining. Garnaut found that the effects of climate change on infrastructure that have not been estimated could subtract an additional 0.8 percentage points from the GNP by the end of the century. These negative impacts on infrastructure have a significant effect on Australia's output and consumption of goods and services, and are responsible for about 40 percent of total climate change costs. The infrastructure impacts affect a wide range of assets, including commercial and residential buildings, water supply and electricity infrastructure, and ports (Garnaut, 2008). Garnaut did not measure the non-market impacts and insurance values, but states that these effects will be very significant in a no mitigation future.

The review recommended that Australia push internationally for CO_2e concentrations of 450 ppm, which would commit Australia to reductions of 25 percent on 2000 levels by 2020, and 90 percent by 2050. It also recommended that Australia have a fallback position of 550 CO_2e concentrations, which would entail a 10 percent reduction in emissions by 2020, and an 80 percent reduction by 2050 (Garnaut, 2008). Garnaut further recommended that, should all negotiations collapse at the Copenhagen Summit, Australia should still reduce its emissions by 5 percent by 2020 on 2000 levels.

Analysis of Mitigation Policies

The Australian Treasury Department published "*Australia's Low Pollution Future: The Economics of Climate Change Mitigation" in 2008, which* presents the results of economic modeling of the potential economic impacts of reducing emissions over the medium- and long-term (Treasury of Australia, 2008). The report found that early global action is less expensive than later action. The modeling indicates that economies that act early face lower long-term costs; around 15 percent lower than if the country delays action until there is international agreement. The report also concluded that average annual GNP growth will only be one-tenth of 1 percent per year less than it would be in a world without action to tackle climate change (Treasury of Australia, 2008).

National emissions targets are based on the per capita allocation approach developed by the Garnaut Climate Change Review. Australia's emissions reduction targets in these scenarios are 10 percent below 2000 levels by 2020 and 80 percent below by 2050 for stabilization at 550 ppm. The targets are 25 percent below 2000 levels by 2020 and 90 percent below by 2050 for stabilization at 450 ppm (Treasury of Australia, 2008). The modeling does not include the economic impacts of climate change itself, so does not assess the benefits of reducing climate change risks through mitigation. Yet the report concludes that average annual GNP growth will only be 0.1 percent per year less than it would be in a world without action to mitigate climate change. The report shows that from 2010 to 2050, real GNP per capita grows at an average annual rate of 1.1 percent in the policy (GHG reduction) scenarios, compared to 1.2 percent in the reference scenario. It states that taking early action will allow an orderly and gradual adjustment to a low-carbon economy, while choosing to delaying action, and then playing catch up, will deliver a sharper shock to the economy in the future (Treasury of Australia, 2008).

The Garnaut review analyzes the three scenarios: the no mitigation scenario, in which the world does not attempt to reduce GHG emissions; and the 550 and 450 ppm scenarios, which represent global efforts to reduce emissions sufficiently to reach those CO_2 concentration levels. The review's economic modeling focused on five areas of impact: primary production, human health, infrastructure, cyclones, and international trade. Climate change shocks were imposed on each area to estimate the likely market costs of climate change (Garnaut, 2008). Expected climate change damages are less in the 450 scenario than in the 550 scenario, but only by half a percent of GNP. The small expected market gain from the 450 scenario to 2100 is not in itself adequate to justify the additional mitigation costs associated with it. Rather, the report states that stronger mitigation is justified by insurance value and non-market value benefits in the 21st century, and much larger benefits beyond, and that the costs of action are less than the costs of inaction (Garnaut, 2008).

The review concludes that there likely will be more technological progress than currently anticipated assuming a significant and rising carbon price, support for the emergence of low emissions technologies, and new policies, such as an emissions trading scheme, are permanent. Such developments would favor a 450 ppm outcome over a 550 ppm outcome. Given the benefits after the year 2200 of stronger mitigation and the greater risks of catastrophic consequences to the natural environment under the 550 ppm scenario, the review judges that it is worth paying less than an additional 1 percent of GNP as a premium in order to achieve a 450 ppm result (Garnaut, 2008).

Australia's Decision Process

While Australia has not utilized a diverse range of economic tools as compared to the UK, the Garnaut review is one of the first of its kind to detail the economics of climate change at a country-specific level. Australia's Minister of Climate Change and Water, Senator Penny Wong, stated that the review, "… shows that while there will be some unavoidable costs from climate change, the costs of taking action to reduce carbon pollution are less than the costs that would be incurred if we fail to act" (Australia, 2008b). The Australian government weighed both the Garnaut review and the Treasury's report on mitigation costs before deciding on a 15 percent reduction by 2020. Senator Wong has also stated that, “the Treasury’s modeling demonstrates that early global action is less expensive than later action; that a market-based approach allows robust economic growth into the future even as emissions fall; and that many of Australia’s industries will maintain or improve their competitiveness as the world moves to reduce carbon pollution” (Australia, 2008a). While the review found that a target of 25 percent reduction was economically feasible, the risks of international competition have kept the government from initially endorsing such a goal. Both the government and Dr. Garnaut have stated that the reduction targets should be increased to 25 percent with a new global agreement in 2009 (Taylor, 2008). If the world cannot agree on Australia’s goals, Dr. Garnaut stated that the country should still aim to cut emissions by 10 percent by 2020, or 5 percent at an absolute minimum (Sydney Morning Herald, 2008).

Case Study 3: California

Overview

California has been at the forefront of climate change research and policy in the United States. In 2007, the California Air Resources Board (ARB) adopted GHG emissions limits as a result of the Global Warming Solutions Act of 2006 (AB32). AB32 establishes the first comprehensive program of regulatory and market mechanisms to achieve quantifiable reductions in GHG emissions in the United States. The law sets an economy-wide cap on California GHG emissions at 1990 levels by no later than 2020. This goal represents approximately an 11 percent reduction from current emissions levels and nearly a 30 percent reduction from projected business-as-usual levels in 2020 (California, 2008a).

Studies of Climate Change Impacts and Economic Costs

The Energy Commission’s Public Interest Energy Research (PIER) Program published “Global Climate Change and California: Potential Implications for Ecosystems, Health, and the Economy,” in 2003 (PIER, 2003a). The report contains a detailed study on the potential effect of climate change on the California economy. The study examines potentially affected sectors and the interactions between climate change and increased population, and economic and technological growth. It considers a wide range of climate change scenarios, varying among temperature and precipitation. Some economic impacts were projected, though many believe these impacts were underestimated. A review of the 2003 study was conducted and discussed the strengths and weaknesses of the PIER 2003 study. The review recommended that the findings be viewed not as specific predictions, but rather as a sensitivity analysis that considers a range of potential outcomes (PIER, 2003b).

In addition, a paper in the Proceedings of the National Academy Sciences (PNAS) released after the 2003 PIER study was considered to be very influential in California’s decision making process. “Emissions Pathways, Climate Change, and Impacts on California”, showed that the level of impacts gets worse with increased global GHG emissions. The study shows the implications and associated impacts in California of the highest and lowest IPCC emissions pathways for climate change (Hayhoe et al., 2004). Under the high emissions scenario, heatwaves in Los Angeles are six to eight times more frequent, with heat-related excess mortality increasing five to seven times. Alpine and subalpine forests are reduced by 75–90 percent. Finally, snowpack declines 73–90 percent, with cascading impacts on runoff and streamflow that, combined with projected modest declines in winter precipitation, could fundamentally disrupt California's water rights system times. While the study did not estimate economic impacts, it has been used as motivation for climate policies that avoid the largest impacts of the high emission scenario (Hayhoe et al., 2004).

Building upon the work of the PNAS study, the 2006 impacts assessment report, "**Our Changing Climate: Assessing the Risks to California" (California, 2006) was stated to be a primary motivating factor in the development of California AB32 (California, 2007).** For this report, PIER developed 20 technical papers analyzing issues such as potential impacts of climate change on agriculture and energy and water resources. These papers include impacts on forest resources, agriculture, water supply management, health impacts, sea level rise, and changes in energy demand. The research served as the basis for evaluations of California climate change impacts at the state government's top levels. While the assessment did not calculate economic impacts, a soon to be published 2008 **impact report (California, forthcoming) will analyze the economic impacts of climate change air quality, public health, forestry, agriculture, and coastal protection. In 2008**, Governor Arnold Schwarzenegger issued a directive mandating the preparation of biennial science reports on the potential impacts of climate change on California (California, 2008a).

Analysis of Mitigation Policies

California recently released the AB32 Scoping Plan, which contains the main strategies California will use to mitigate GHG emissions (California, 2008a). The Scoping Plan contains a range of GHG reduction policies and measures, which include direct regulations, alternative compliance mechanisms, monetary and non-monetary incentives, voluntary actions, and a economy wide cap-and-trade system. Included as an appendix to the Scoping Plan was an economic analysis, which contains an assessment of the economic impacts of the recommended measures in AB32 (but not an analysis of the value of avoided damages from climate change). **California modeled the economic costs of AB32 and found benefits to the economy from mitigation, in addition to the avoided costs of climate impacts (California, 2008b). This provided further motivation for a portfolio of mitigation policies.** The Scoping Plan also contains a section that describes the costs and benefits of the market-based compliance mechanisms.

California's Decision Process

As a direct result of PIER's 2006 impact assessment, Eileen Wenger Tutt of the California Environmental Protection Agency stated, "The quality of research contained in the scenario analysis performed by PIER far exceeded our expectations. The findings of the report contributed greatly to our understanding of the effects of climate change emissions in California. These findings were the basis of the scientific evidence reflected in the March 2006 Climate Action Team report and in AB32, the California Global Warming Solutions Act of 2006" (California, 2007). By collecting information on the potential impacts of climate change, the State apparently developed motivation to set emissions reduction goals that surpass any other state in the country, and even surpass many developed countries' goals, despite a lack of a federal policy on climate change.

Policymakers in California also found benefits in the state taking pre-emptive action, even though climate change mitigation will require global action. California policymakers also acted because state industries could gain significant advantage from the state's "first mover" status (California, 2008b). These benefits include job creation, investment opportunities from outside sources (California is the leading recipient of venture capital for low-carbon technology in the world), and a chance to be rewarded for taking early action when more comprehensive federal or global climate agreements are developed.

Conclusions

This report briefly examines the role that the analysis of potential economic losses from climate change played for three governments: the United Kingdom, Australia, and the State of California, in providing support for GHG emissions reduction policies. While it appears that none of the governments undertook a formal benefit-cost analysis using the future benefits of avoided climate change to set its GHG reduction targets, it appears that the estimation of the benefits of avoided impacts may have played a role in justifying climate policies. However, it is also possible that the levels of emissions reductions selected by each government would have been selected even if formal economic analysis of the benefits of such reductions had not been done.

Impacts studies have provided useful information enabling all three governments to help support long-term GHG emissions reduction targets. Using integrated assessment models, the UK government concluded that the dangers of global unabated climate change will be equivalent to at least 5 percent of GDP each year, and could possibly rise to 20 percent of GDP or more if a wider range of risks and impacts are taken into account. In contrast, the costs of action to avoid the worst impacts could be limited to around 1 percent of global GDP if the world pursues optimal policies (Stern, 2006). The analysis by Stern, which does not explicitly look at avoided damages but compares the costs of inaction against the cost of taking action, was used as motivation for Britain's recent adoption of Climate Change Act targets. The government also found that the cost of meeting the Act's proposed budgets is less than 1 percent of GDP in 2020 (CCC, 2008a).

Impacts of changes in climate[5] have already been felt throughout the Australian economy and this appears to have played a key role in the Australian government adopting GHG

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[5] It is not clear whether such changes can be attributed to anthropogenic climate change.

emissions reduction targets. The government commissioned the Garnaut review to examine how much mitigation is justified. The review compared the costs of mitigation with the benefits of climate change avoided by mitigation using integrated assessment models. The review found that the overall cost to the Australian economy of tackling climate change would be in the order of 0.1-0.2 percent of annual economic growth to 2020. The review estimated that global GNP would decline around 8 percent by 2100 from climate impacts, with losses in developing countries likely to be higher than the global average (Garnaut, 2008).

In California's case, policymakers acknowledged that previous impacts assessments were a key motivation into passing legislation on an ambitious emissions reduction target. Yet, these impacts assessments focused on physical and biological impacts such as loss of snowpack and increase in deaths from excess heat. The next impacts assessment will provide greater economic details on economic damages from business-as-usual emissions on a sector by sector basis.

The three governments studied in this report are all leaders in pledging to substantially reduce future GHG emissions. Each of them have also been leaders in assessing the impacts of climate change. Two, the UK and Australia, have estimated the total value of economic losses from climate change. The third, California, has conducted extensive analysis of climate change impacts. The UK and Australia concluded that substantial reductions in GHG emissions would cost less than the impacts of climate change, while California did not make such a calculus. In spite of this, it does not appear that emissions reduction targets were based on a formal application of benefit-cost analysis. For example, none of the governments calculated economically optimal emissions reductions, e.g., where the marginal benefit of emissions reductions is equal to the marginal cost. Instead, it appears that the calculation of economic losses from climate change (or in the case of California description of projected impacts) was useful to and informed the policy process. The setting of targets was apparently based on a number of considerations, such as cost-effectiveness and competitiveness, not just avoided economic impacts.

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Background Papers for Session 2:

Challenges to Quantifying Damages from Climate Change

WORKSHOP PROCEEDINGS

Assessing the Benefits of Avoided Climate Change: Cost-Benefit Analysis and Beyond

Challenges to Providing Quantitative Estimates of the Environmental and Societal Impacts of Global Climate Change

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Challenges to Providing Quantitative Estimates of the Environmental and Societal Impacts of Global Climate Change

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Abstract

As the impacts of climate change become more apparent and the prospects grow for more severe impacts in the future, policy makers are intensifying their efforts to craft an international agreement to "prevent dangerous anthropogenic interference with the climate system."[1] Equally daunting, however, is developing and implementing the domestic policies needed to achieve the goals set forth in such an agreement. In formulating environmental regulations in the United States, the most commonly used analytic approach is to weigh the costs of control measures against the benefits (or reduced costs) resulting from reducing environmental and societal damage. Within this cost-benefit framework, it is argued that no more should be spent to reduce pollution than the resulting economic benefits would yield.

However, complexities of the climate system and its linkages with society complicate the development of accurate estimates of the costs and benefits of a given policy to address climate change. This paper presents, from the viewpoint of a climate scientist, an overview of the key challenges to understanding and incorporating in policy analyses the impacts of climate change for specific regions and on shorter time scales. While not attempting a comprehensive evaluation, this paper emphasizes those aspects of the Earth system and its connection with human society that introduce challenges for economic analyses of climate change impacts. It also suggests a minimum set of impacts that might be useful to consider in quantitative policy analyses; beyond these, there are many potential impacts, some catastrophic, that would be better considered using a risk-based approach rather than a cost-benefit analysis.

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[1] Article 2, United Nations Framework Convention on Climate Change, 1992.

1. Introduction

Over the past 150 years, human activities have increased the atmospheric concentrations of carbon dioxide (CO_2) and methane (CH_4) by over 35 percent and 150 percent, respectively. The concentrations of other greenhouse (heat-trapping) gases have also increased (Forster and Ramaswamy, 2007). The climate of the world has started to respond:

- Global average temperature has risen about 0.8 °C (1.4 °F) since 1850 (Trenberth and Jones, 2007; Hegerl and Zwiers, 2007);
- Minimum summer sea ice extent in the Arctic has decreased about 21 percent since 1979 (Serreze et al., 2007);
- Mountain glaciers and the Greenland and Antarctic ice sheets have started to lose mass (Dyurgerov and Meier, 1997; Chen et al., 2006; Cook et al., 2005; Alley et al., 2008; Rignot, 2008; Rignot et al., 2008);
- Sea level has risen by about 0.2 m (0.7 ft), and the rate of rise in the early 21st century is about double the average rate for the 20th century (Bindoff and Willebrand, 2007);
- Both the broad mid-latitudinal bands of precipitation and the dry subtropical bands have started shifting poleward (Zhang et al., 2007; Milly et al., 2008).

When viewed as global averages, these changes and others seem to occur slowly, leaving the impression that climate change in general is likely to proceed in a slow, steady fashion. This impression leads to the common presumption that there will be ample time to prepare for climate change and its associated impacts. Such a delay in facing impacts would, it is argued, allow time for the economy to adjust gradually, with slow emissions reductions and gradual planning and implementation of adaptation measures. But is this assumption about slow, steady climate change really true?

Because scientists typically average climate variables (e.g., temperature or precipitation) over long time periods (~30 years) and over large regions, reported climatic conditions are likely to continue to appear to change slowly. On the other hand, the actual impacts are likely to be more sudden and more concentrated in particular locations. For example, storms, which often have dramatic local impacts, are likely to become more intense (Meehl and Stocker, 2007). Around the world, observations indicate that a larger fraction of rain is coming in downpours[2] (Trenberth and Jones, 2007; Aumann et al., 2008) and that an increasing fraction of tropical storms (i.e. hurricanes, cyclones, and typhoons) are

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[2] With more of the precipitation occurring in downpours, the fraction of precipitation that runs off tends to increase, more rapidly filling streams and rivers. When falling on snowpack, heavy downpours increase the melting rate. Such episodes increase the likelihood of flooding (Groisman et al., 2004).

intensifying toward the most powerful categories[3] (Elsner et al., 2008). Conversely, longer intervals between significant rains are leading to prolonged periods with increased evaporation and therefore more periods with dry soils and drought (Meehl and Stocker, 2007). In addition to agricultural losses and disrupted water supplies, one consequence of prolonged dryness is an increase in the frequency and intensity of wildfire, which is already occurring in western North America (Westerling et al. 2006; Bachelet et al., 2007).

High and low daily temperature extremes also shift in both magnitude and frequency as the climate changes (Chritensen and Hewitson, 2007). Greenhouse-gas-induced warming tends to shift daily temperatures to a higher average value,[4] which leads to a disproportionately larger increase in the likelihood that, for example, the high or the low temperature of a particular day or a sequence of days is above a particular threshold value, such as the local temperature above which heat is considered extreme. Consequently, the frequency of heat waves and heat-induced deaths can greatly increase, especially in urban areas and regions where air-conditioning is not widespread and the population has not had time to acclimate to heat extremes (Ebi and Meehl, 2007).

The most important near-term impacts are likely to result from changes in local weather extremes rather than the slow changes in global or regional long-term averages (e.g., IPCC, 2007b). For example, particularly significant consequences can result from local increases in maximum and minimum temperature, storm surge height with resulting inundation and coastal erosion, transition into repeated or persistent drought with a resulting increase in the frequency of wildfire, intense rainfall that results in flooding and landslides, higher minimum temperatures that lead to pest survival and tree death, and reduced snowpack that leads to changes in the timing of snowmelt and runoff. These sporadic changes in extreme weather will lead to significant impacts to the environment and to societal infrastructure and well-being.

In the context of analyzing mitigation policies, evaluating the potential impacts of climate change requires special attention to short time scales and intermittent—even rare—extreme events. As an example, the most intense rains fall in regions of complex topography, creating flooding along particular river systems, while drought and hot weather combine to create fires in certain regions, and hurricanes strike in other locations. So that society can be safe and function effectively, design and building standards have been crafted to greatly limit the damage below chosen thresholds of weather extremes

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[3] Because tropical cyclones are becoming more powerful, they are expected to lead to higher and stronger storm surges with greater damage and more frequent inundation; furthermore, sea level rise means that less intense storms can also lead to inundation.

[4] Day-to-day variations in the weather about the long-term average are generally distributed in the shape of the familiar bell curve. For example, daily high temperatures for a given month tend to be distributed in this way, with the average representing the average daily high temperature for that month and the width of the bell curve representing the degree of variation. Daily low temperatures form a similar curve. As the climate changes, both curves tend to shift toward higher values, increasing both high and low extremes.

(e.g., many structures are designed to withstand a one-in-a-hundred-year flood—based on the historical record).

As gradual climate change shifts the statistical envelope that bounds the intensity, range, scale, and duration of weather extremes, intense events that can cause significant damage are projected to become much more likely. The result is that large areas are likely to be more frequently exposed to conditions that exceed existing tolerance thresholds (e.g., ecological, precipitation, temperatures, and sea level) to which the environment and society have become accustomed over long periods of time. *The nonlinearity of the results can greatly complicate estimation of the likely impacts of climate change and the benefits of taking particular policy actions.*

With increasing attention on the relative merits of various policies for cutting greenhouse gas emissions, decision makers are likely to expect more and more detailed results from cost-benefit analyses (CBA) and integrated assessment models (IAM).[5] As climate change intensifies and generates a greater variety of impacts, and as the degree of change further exceeds historical norms, preparing such analyses in a convincing way will become more and more difficult. Several chapters in IPCC (2007b) and earlier IPCC assessments address the strengths and weaknesses of cost-benefit and other approaches for evaluating the implications of climate change on global to regional scales. In general, the results of these evaluations suggest that risk-management approaches are superior to CBA for dealing with the complexity of the Earth system and the inherent uncertainties arising from trying to project ahead a century and more.

The next section describes how the most important complications create systemic problems for moving from global to regional and local scale damage functions to represent the costs of future consequences. In that U.S. attention is likely to focus on U.S. impacts, the third section describes the challenge of estimating costs and benefits (i.e. of developing a quantitatively rigorous damage function) for just the United States. The fourth section suggests an alternative approach to such analyses, laying out a minimum set of climate change impacts that should be considered in estimating the significance of climate change for society. Policies costing less than the benefits gained by avoiding these impacts would seem to be favored. In addition to these baseline impacts, however, many additional risks have the potential to introduce additional complexities into the decision process and will need to be considered through the lens of risk management.[6] The concluding section offers thoughts on moving forward and on the importance of the decisions being made as governments move to develop implementation policies.

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[5] See the papers by Ackerman et al. and Mastrandrea in this volume for detailed background on cost-benefit analysis and integrated assessment models.

[6] See the paper by Yohe in this volume for detailed discussion of risk management.

2. Systemic Problems with Estimating the Economic Costs of the Future Consequences of Global Climate Change

Many public policy decision processes involve the weighing of the costs and benefits of particular actions. For decisions that involve well-defined steps and consequences, typically focused on the near-term and on limited spatial domains, the technical basis and art of conducting such studies have developed over recent decades.[7] While criticisms and problems remain, such efforts have often been illuminating in deciding among various courses of action, particularly for marginal improvements.

The choice of a discount rate illustrates one important problem with cost-benefit analyses as applied to climate change policies. Use of a discount rate is the traditional approach to deriving the net present value (or expected ultimate economic cost) of an investment, including the environmental and societal consequences projected to occur in the future (e.g., over the operational and depreciable lifetime of a major energy facility). In such analyses, the higher the discount rate, the greater the weight given the present and near future as opposed to the long term. Because many climate change impacts develop over time and lead to consequences far in the future, the long-term costs (and uncertainties in their determination) tend to become obscured when even a modest discount rate is used. This has the effect of deemphasizing the accumulating long-term significance of climate change and the increasingly significant consequences that will face future generations due to greenhouse gases emitted today. While the differences in viewpoint and results in the analyses of Stern (2007) and Nordhaus (2007) are in large part due to the differences in their economic assumptions, other differences also arise because long-term changes in the atmospheric, oceanic, terrestrial, and biospheric components of the Earth system (and their uncertainties) play an especially significant role when the discount rate is low.

This section describes some of the inherent problems with evaluating climate change impacts and their global implications. (Additional problems with estimating the impacts of climate change for the United States or a smaller geographic region are considered in the next section). Many of the problems described here appear to be inherent to the complexity of the Earth system; uncertainties from these problems are therefore likely to persist in spite of future advances in understanding. The challenges are grouped below into two broad categories: (1) challenges arising from characteristics of the atmospheric, oceanic, cryospheric, and biospheric components of the climate system, including limits in scientific understanding of how to project the future climate; and (2) challenges arising from the interactions of society with the climate system. Although many of the specific examples refer to the United States, such examples can be found all around the world, and all nations will need to deal with these limitations as efforts intensify to limit emissions and adapt to unavoidable changes.

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[7] See the paper by Ackerman et al. in this volume for background on cost-benefit analysis.

2.1. Characteristics of the climate system

In many discussions, the limitations in understanding climate change are often lumped with statements about uncertainties in the climate sensitivity, which is defined as the equilibrium warming that would result from a doubling of the CO_2 concentration in the atmosphere. The IPCC Fourth Assessment (IPCC, 2007a), for example, found that "the climate sensitivity is likely[8] to be in the range 2 °C to 4.5 °C, with a best estimate value of about 3 °C," and that it is "very unlikely[9] to be less than 1.5 °C." The implication is that global average temperature can be projected to within about 50 percent (i.e., the sensitivity is essentially 3 ± 1.5 °C). Using the climate sensitivity as the single measure of the uncertainty in scientific understanding of climate change, however, is misleading. First, the observational record does not allow the upper bound of the climate sensitivity to be as well established as the lower bound—in fact, some approaches to estimating the climate sensitivity suggest that it could be higher than 4.5 °C. Also, the historical and paleoclimatic records provide insights into the climate system that allow a deeper appreciation of the levels of uncertainty and confidence in various findings than can be gained from consideration of the climate sensitivity alone.

Most serious of all, however, is that the climate sensitivity is not particularly helpful in making quantitative estimates of the impacts of climate change and of their significance and uncertainty. Evaluating impacts requires information on the rate, magnitude, and location of changes in the broad set of factors that define the climate. Unfortunately, developing such estimates reveals many complexities in the climate system that greatly increase the uncertainty of cost-benefit analyses. Among the most important are the following:

1. **Both climate change and the resulting impacts typically have a strong local component, making generalization difficult.** Geographic features, resources, and development can combine to create significant local and regional differences in the effects of climate change, especially because resilience and vulnerability tend to vary by location and adaptive capacity. Cost-benefit analyses largely fail to capture impacts on local ecosystems, communities, and facilities, and local decisions regarding land use and development can play an important role in the severity of impacts.[10]
2. **Greenhouse gas emissions cause impacts in both the near and long term, but different greenhouse gases persist in the atmosphere for different time periods.** For long-lived gases like CO_2, impacts could persist for centuries or longer (Solomon et al., 2009; Charbit et al., 2008). Failing to include in the analyses the long-term implications of near-term actions would yield a very incomplete and misleading portrayal of their significance.

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[8] The IPCC defines "likely" as better than 2:3 odds.

[9] The IPCC defines "very unlikely" as less than 1:10 odds.

[10] See the paper by Ebi in this volume.

3. **Response of the climate system lags behind actual emissions, and response time differs among systems.** This means not only that an impact analysis would be starting from conditions that do not reflect the full consequences of past emissions, but also that the impacts of future emissions (including reductions from policy actions) will extend far into the future and will be very hard to distinguish from the continually developing responses to past emissions.
4. **Impacts result from natural climate variability in addition to human-induced climate change.** Distinguishing the fraction of damages to associate with the influence of human activities will not be sufficient, because the human influence is on top of the natural component and relationships are nonlinearly coupled and dependent on each other. With the human contribution to climate change increasing over time, with ongoing natural variability (the variability of which may be altered by human activities), with sea level rising due to human activities, and with the couplings and processes being nonlinear, distinguishing the consequences of human-induced climate impacts from effects that would have occurred naturally without climate change is very likely to involve significant uncertainties, especially when there are synergetic interactions between natural and human-induced climate phenomena.
5. **A number of impacts of climate change are projected to be irreversible or virtually irreversible** (IPCC, 2007a; 2007b). For example, warmer temperatures may persist for at least 1000 years without returning to preindustrial levels (Solomon et al. 2009). Polar and high-altitude species are likely to be pushed to extinction as their habitats disappear.
6. **The climate system is nonlinear, and thresholds are likely to be exceeded beyond which damages increase dramatically.** Examples include increased heavy downpours, the duration and severity of droughts and heat waves,[11] the melting of permafrost and sea ice, the loss of mass from the Greenland and Antarctic ice sheets, the likelihood and intensity of flooding,[12] and the spread of pests and loss of forests (ACIA, 2004; IPCC, 2007b). Detailed projections of the impacts need to consider the chaotic behavior of both physical and social systems, something particularly difficult to handle in cost-benefit analyses.
7. **The complex and nonlinear nature of the climate system increases the likelihood of surprises.** Because of the potential for surprises and extremes, the probability of which cannot be objectively estimated, there is a strong likelihood that

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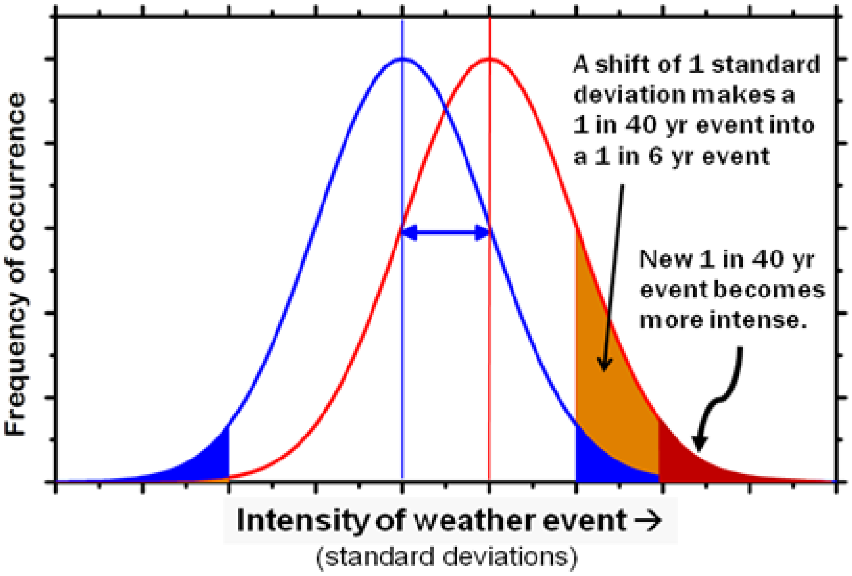
[11] For some species (e.g., some crops), warming can have no or even positive effects until a temperature threshold is exceeded, and then very significant negative consequences can result. In cities, when weather conditions exceed the design criteria for healthy conditions in buildings, there can be a sharp increase in cases of heat stress.

[12] In southern Florida, for example, the underlying geology is such that levees would eventually fail, leading to inundation (Miami-Dade County Climate Change Task Force, 2007). In the Northwest, a slight lengthening of the warm season and increase in minimum winter temperatures has led to near total loss of major forest areas to greatly amplified infestations of the pine bark beetle.

actual impacts and their importance will be underestimated in cost-benefit analyses (Weitzman 2009).

8. **Weather, not climate, is what is actually experienced at a given location and time; historical extremes, and worse, will become more commonplace as the climate changes.** Shifts in the bell-shaped distribution of weather conditions will alter the frequency of extreme events, often sharply (Fig. 1; Christensen and Hewitson, 2007). A shift in the average leads to a much greater likelihood of exceeding certain temperature and precipitation thresholds (Battisti and Naylor, 2009).[13] Given that extremes result in most of the damage, uncertainties in estimating the likelihood and thus costs of extremes are likely to be particularly large and important.

Figure 1. Simplified depiction of the changes in temperature and precipitation in a warming world. *(Adapted from CCSP, 2008*



9. **Climatic regimes are shifting, causing extreme weather events in unlikely places and rendering the historical record useless in predicting future climate in some places.** Estimating the timing and severity of impacts (particularly at the moving edges of climate regimes) is problematic,[14] and averaging over these effects would

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[13] For example, the Canadian Climate Model suggests that in 100 years, today's 1 in a 100-year flood will likely be occurring every 30 years, and today's 1 in every 300-year flood will likely be occurring once every 100 years (Zwiers and Kharin, 1998). Most infrastructure has been designed based on the frequency of extremes in the past, and it will not be easy to upgrade many facilities without replacing them (e.g., bridges built to withstand a 1 in a 100-year flood).

[14] For example, will a hurricane causing a storm surge that floods Miami or New York occur within a few years or not occur for a few decades? Here the choice of the discount rate will make a striking difference in the net present value of the impact.

seem likely to grossly underestimate the significance of low probability, high consequence events in particular places (Weitzman 2009).

10. **The ocean is becoming more acidic as a consequence of absorbing excess atmospheric CO_2, with potentially severe consequences for marine life and associated effects for society** (Orr et al., 2005; Monaco Declaration, 2009; Raven, 2005). While some attempts have been made to quantify the economic value of coral reefs (Brander 2009) in particular, these analyses largely neglect some important impacts that are not easily monetized. The non-market impacts on ecological services provided by marine life, such as coastal protection by coral reefs, subsistence fishing in island and developing nations, and ecosystem diversity and resilience, would not seem to be representable using the traditional cost-benefit analysis.[15]

2.2. Characteristics of society and its linkages to the climate system

In addition to the complexities of the climate system itself, a useful estimation of long-term impacts must allow for the ongoing development of society over time, including its responses to climate change impacts. Developing realistic estimates of the costs and impacts of climate change and mitigation policies is challenging due to the long lifetime of greenhouse gases and investments in infrastructure, along with complex linkages between society and the environment. Among the most important are the following:

1. **Global environmental and social systems are both very complex and interdependent, and ecological services are often assumed to be substitutable by technology.** However, the value of many such ecological services, such as cleansing of air and water, regeneration of oxygen, and sustaining biodiversity, which have been estimated to be roughly comparable in value to the beneficial services of the global economy (Costanza et al., 1997), are not replaceable by technology on anything but a very small scale. Due to limits in understanding of the environment and of societal dependencies, only the simplest representations of the linkages and their economic significance have the potential to be included in cost-benefit analyses.
2. **Increasing atmospheric concentrations of greenhouse gases and the resulting changes in climate and ocean acidification are not the only human influences on the environment.**[16] Assigning consequences among the various stresses would need to vary by location, the intensity of the individual stresses, the time history of the influences, characteristics of the local situation, etc. In many cases, climate change is increasing vulnerability to other stresses. Determining how best to separate out the

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[15] See the papers by Ackerman, Mastrandrea, Rose, and Yohe in this volume for background on non-market impacts.

[16] Coral reefs, for example, face threats due to contaminants, coastal development, fish harvesting, and recreational use, along with the impacts of warming, sea level rise, and ocean acidification. Terrestrial systems face stresses created by land cover change, invasive species, human-produced chemicals, and so on.

contributions of climate change, and then of climate change policies, is likely to create significant uncertainty as well as disagreement among different attempts to construct such estimates.

3. **The impacts from climate change will be complicated by human decision making.** Projection of societal development is predicated on a set of emissions and behavioral scenarios. In the case of disasters such as hurricanes and wildfires, preparedness by citizens and responsiveness by governments will affect the severity of impacts. All levels of decision making, from individual to local and national governments, both near-term and long-term, have the potential to influence the severity of impacts.

4. **The effects of climate change raise serious equity issues—geographically, socio-economically, and generationally.**[17] In attempting to deal with the problems of equity that arise across incomes, communities, nations, and generations, uncertainties created both by climate change and societal development complicate both projections of climate change and the weighting and aggregation of impacts.

5. **The potential for adaptation must be considered in estimating impacts.** Adaptive measures to reduce impacts, such as the construction of sea walls to protect against rising sea levels, can reduce impacts from climate change (Tol, 2007). However, climate change is likely to overwhelm some adaptation strategies, eventually forcing retreat (Yohe et al., 2007). A critical issue is going to be whether retreat is going to take place before or after disaster.

6. **The impacts of climate change also depend on rates of societal change and technological improvement.** Since the ability to make accurate societal (i.e., demographic parameters such as location, age, profession, wealth, size, vulnerability) and technological (i.e., capabilities, cost, efficiency, availability) projections is at least as limited over the long-term as for climate, uncertainties in social development will likely be more reliably addressed in a probabilistic sense than in a deterministic framework.[18]

7. **Geoengineering has the potential to limit impacts, but very little is known about the potential for adverse side effects.**[19] Evaluation would be needed not only of the impacts that geoengineering might be able to moderate (Caldiera and Wood, 2008), but also of the potential unintended consequences as well as the likely persistence

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[17] Those suffering the largest impacts, some of which may well be irreversible, tend to be the poor, whereas those experiencing benefits are richer, both individually and on a national basis. A similar situation exists in time—those living today are likely to suffer relatively modest consequences, whereas those living in the future, who have no voice in decisions made today, are likely to experience larger consequences. (See, for example, the statement of the U.S. Conference of Catholic Bishops, at http://www.usccb.org/sdwp/international/globalclimate.shtml.)

[18] See the papers by Mastrandrea and Rose in this volume for discussion of deterministic vs. probabilistic analyses.

[19] In addition to the potential for adverse side effects, no geoengineering approach (or set of them) appears to be capable of counter-balancing all negative impacts.

and effectiveness of the required governance structure extending far into the future. With the pace of climate change accelerating and projections indicating that "dangerous anthropogenic interference with the climate system" may be imminent, calculation of the global benefits and impacts in detail is likely to be especially difficult and uncertain.

Together with the problems relating to economic formulation in cost-benefit analyses (not considered here), the complexities of the climate system and its coupling to society should prompt exploration of alternative approaches for evaluating policy options.

3. Special Complications for Estimating Consequences for the United States

In addition to the global-scale and systemic challenges identified above, a number of additional issues arise in identifying uncertainties resulting from impacts affecting the United States or regions within the US. This section provides an overview of these special challenges:

1. **The United States is part of a global community—neither the natural world nor the global economy can be readily separated at the U.S. border.** The nations of the world are interconnected through trade (including climate-dependent products and services, such as food crops and water-intensive products); environmental resources (e.g., fisheries, migrating species, and freshwater in lakes and rivers); human health (e.g., through various disease vectors, such as West Nile virus, flu epidemics, etc.); familial and ethical connections (e.g., as a result of previous immigration, remaining family connections, historical linkages, work experience, etc.); and national security (since environmental disruption can cause regional dislocations and act as a threat multiplier). Quantifying climate change impacts for the United States thus requires quantifying impacts around the world.
2. **The United States is more than the 50 states—it includes Indigenous Peoples, Native Americans, Caribbean Islands, and Pacific Islands.** The complexities of the United States—its multilevel and distributed government structure and its natural and developed environments—are likely to make it difficult to generalize the national impacts of climate change. For example, Native Peoples face more impacts than the general population because their activities and lifestyles are more directly connected to the environment (NAST, 2000; ACIA, 2004).
3. **Democratic systems generally tend to be more reactive than proactive in responding to environmental problems and threats** (Healy and Malhorta 2009). Economic estimates should account for delays in addressing impacts, including the acceleration of environmental damage during the period of delay, and the presence of thresholds over which the impacts are likely to develop before being addressed.

4. **The complexities of land ownership and responsibility pose unique obstacles to policy implementation.** Because of the large fraction of private land and financial ownership,[20] the distributed nature of government, and the limited ability of government to affect behavior, it is likely to take longer to adapt to climate impacts than the perfectly rational response that cost-benefit analyses typically assume.[21] For example, along many rivers and coasts, the response to flooding and inundation has been to rebuild instead of retreat, although retreat may ultimately be necessary in many areas.
5. **The potential exists for the United States to allow or bar entry of environmental refugees into the country from other parts of the world facing climate disasters.** With most growth in U.S. emissions resulting from the increase in population (which in turn results in the need for additional homes, infrastructure, and services) projecting actual immigration will be important but problematic for quantifying impacts, partly because it can be affected by migrations from disasters abroad (e.g., Hurricane Mitch in 1998) and in the United States (e.g., Hurricane Katrina in 2005 and southern Mississippi River flooding in 1927).
6. **The United States has a tremendous investment in its existing infrastructure (e.g., roadways, railroads, sewage treatment plants, and entire cities) that are exposed to a range of potential impacts from changes in climate and extreme weather.** Much of this infrastructure is located on low-lying coasts where protection from rising sea level and storm surges is ultimately likely to be more expensive than relocation. The unique situations of each location will make estimation of overall impacts quite difficult, especially when considering issues and costs of relocation and rebuilding. In addition to the physical costs, there are also many complex social costs and implications that merit inclusion (e.g., GAO, 2004).
7. **Because human-induced climate change is a result of the collective actions of the nations of the world, integrated over time, the result of any individual domestic policy action is very likely to look quite modest.** While domestic actions may seem small compared to the scope of the problem, the collective *in*action of all nations will ultimately destroy the value of the commons for virtually every nation (Hardin 1968). To avoid getting tied up in evaluation of the value of a multitude of limited domestic actions, effective analyses must evaluate the adequacy of the overall national policy on climate change in the context of the responses by other nations. Subdividing the evaluation into analyses of the costs and benefits to the United States

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[20] In the UK, where all land is held under a dispensation of the monarch, a national policy not to build right on coastal lowlands quickly had an important effect around the nation; were such a regulation issued by the U.S. government, political and legal reactions would delay its effect.

[21] See the paper by Ackerman et al. in this volume for a discussion of the "rational actor" assumption.

without including the response of the global community is not likely to be particularly helpful for deciding among specific policy options.[22]

8. **The scope of the action required is enormous.** There really is no other option than all nations doing all that they can to reduce emissions as promptly and aggressively as they reasonably can (MacCracken 2008). Carrying out detailed impact analyses of the marginal cost-benefit of imposing specific policies is likely to require significant effort for very limited insight. Instead, a better approach would be to evaluate only the comparative costs of implementing alternative policies seeking to achieve some specific outcome without trying to make detailed comparisons of the full cost implications of impacts due to climate change.[23]

The scientific basis for conducting cost-benefit analyses remains tenuous, but consideration of climate policies in the near future would traditionally require such analyses. Neither the National Assessment completed in 2000 (NAST, 2000), the Arctic Climate Impacts Assessment completed in 2004 (ACIA, 2004), nor the recently released assessment of the U.S. Global Change Research Program (Karl et. al., 2009) have attempted an economic analysis of the impacts within the United States. In lieu of a full analysis, leading economic models have generally either used a parametric curve to represent impacts or attempted to calculate the impacts of public policies using only very large-scale approaches to representing the largest impacts (Mastrandrea, 2010). Neither of these choices would seem to be satisfactory for a serious rule-making analysis

Given the complications outlined above and the limited research support available, the problems with traditional cost-benefit analyses seem likely to persist in the near future. The next section suggests an alternative approach.

4. Formulating a Minimum Set of Risks for the United States

Although it cannot provide a bottom-line estimate of the significance or costs of the impacts (or at least those that would be alleviated by a particular policy action), a list of the most serious consequences can provide an indication of the range and significance of the risks of global climate change. As a starting point, the value to society of ecological services and natural capital has been estimated to be roughly equivalent to the services provided by the world economy (Costanza et al., 1997), and the most important and direct impacts of climate change have been estimated to amount to several percent of that amount (Stern, 2007).

Drawing from four extensively reviewed scientific impacts assessments [the U.S. National Assessment (NAST, 2000), Arctic Climate Impacts Assessment (ACIA, 2004),

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[22] See the paper by Rose in this volume.

[23] See the paper by Ackerman et al. in this volume for discussion of the appropriate role of economic analyses in climate policy.

Intergovernmental Panel on Climate Change (IPCC, 2007b), and the Unified Assessment of the Climate Change Science Program (Karl et. al., 2009)], this section provides an overview of the most important consequences likely to affect the United States.[24] The selected impacts provide a minimum set for consideration in evaluating the relative merits and effects of various policy actions—any policies with costs less than the damage resulting from these minimum impacts would easily be deemed cost effective. Benefits of action beyond those listed here would justify additional costs (Lester and Smith, 2010).

The consequences that are likely to be most disruptive and economically costly for the United States (including its states, tribal lands, territories, and trusts) include the following:

1. **An increase in extreme weather.** Observations show, for example, an increase in the frequency of heavy downpours (Trenberth and Jones, 2007) and in the strength and overall destructive power of hurricanes (Emanuel, 2005; Elsner et al. 2008). The increasing intensity of rain and shifting precipitation bands will likely increase the frequency and extent of flooding, which, combined with increasing populations and infrastructure in vulnerable regions, will greatly amplify damage. Because of experience in estimating damage from past storms, damage from a greater frequency of intense storms could, for example, likely be projected using regionally resolved models to simulate the details of likely changes in the character of extreme weather. Such models are only beginning development and do not inform current economic analyses.
2. **Increased inundation in coastal regions.** Several recent studies project that the total rise in global sea level[25] during the 21st century could be as much as 3 to 6.5 feet (Rahmstorf et al., 2007; Pfeffer et al., 2008; Vermeer and Rahmstorf, 2009). Exposure is high.[26] Although some protection is possible (e.g., storm surge barriers to protect Manhattan and interior New York City), there is no practical way to protect some populated coastal areas and barrier islands (e.g., Brooklyn, Long Island, and the Florida and Texas coasts). Ultimately, retreat will be necessary, which is feasible for individuals but costly for structures and communities (GAO, 2004). The economic, psychological, social, and dislocation costs are likely to be much larger when retreat is in response to a disaster.
3. **Increased stress on water resources, storm runoff, and sewage systems.** Impacts on water resources were the primary concern of virtually all of the regions

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[24] To avoid cluttering the text, specific referencing of these assessments is not included throughout this section.

[25] The consequences of sea level rise tend to become most evident during especially high tides or storm surges caused by tropical storms, and in regions where coastal margins are sinking. Although little damage will result from a small rise in sea level, much more extensive damage can be expected once natural and human barriers (e.g., dunes, mangrove swamps, rock barriers, and sea walls) are overcome.

[26] While Hurricane Katrina showed the vulnerability of New Orleans, there are many other exposed regions, including the Chesapeake and San Francisco bays, the Sacramento-San Joaquin Delta in California, and New York City and Boston harbors.

participating in the U.S. National Assessment (NAST, 2000). Climate change affects water resources by shifting tracks, intensity, and timing of storms (thus altering precipitation patterns) and by reducing the snowpack that feeds reservoirs. Increased storm intensity could more frequently exceed the capacity of storm sewer and runoff systems, and higher sea level can require the modification or relocation of water and sewage treatment facilities. In some regions increased drought will render current water storage and planning approaches inadequate.

4. **Accelerating changes in land cover.** Land cover provides society with a wide variety of ecological services and economic benefits[27] and is affected by climate change.[28] Changes in land cover are affecting or will affect many regions in the United States, such as the Pacific Northwest (pine beetle infestation), southern California (faster growth of plant species[29] that provide more fuel for wildfires), the Southeast and Southwest (drought stress, which increases vulnerability to wildfires), and the Northeast (shifting of species like the sugar maple into Canada). Because the shift from one ecosystem to another takes decades, the transition brings risks and costs.[30] The most direct costs (e.g., fire-fighting, loss of lumber, etc.) can generally be readily estimated but the indirect losses involving social disruption and regional character changes are more difficult to assess.
5. **Increasing stress on wildlife and biodiversity.** Wildlife has evolved in conjunction with the climate and landscape and faces shifting or loss of habitat as a result of climate change and societal development.[31] Projections suggest a substantial decrease in biodiversity as species are pushed past their limits to shift and adapt (Thomas et al., 2004).[32] Experience has been, for example, that removing single species has actually led to quite significant changes in habitats (e.g., removing the wolf in the western United States allowed grazing animals to multiply, leading to changes in land cover), and introduction of new species (especially if invasive) can also dramatically change

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[27] These include, for example, wood and fiber products, soil and coastline stabilization, water purification, air cleansing, aesthetics, recreation, and jobs.

[28] Land cover is dependent on prevailing climate through the character of vegetation and soil.

[29] The increasing CO_2 concentration is likely leading to faster growth of the chaparral that covers the hills and mountains of the region (NAST, 2000), thereby more rapidly building up the mass of dry brush that becomes the fuel for intense wildfires.

[30] The loss of a prevailing ecosystem is likely to be much more rapid than the growth of a new ecosystem. With the pace of climate change accelerating, the time and climatic stability that allow new relationships to develop is lost.

[31] Climate change is leading to poleward and upward shifts in the ranges of species on land (e.g., butterflies, birds, etc.), in rivers (fish, etc.), and in the oceans (e.g., fisheries, anadromous fish, whales). Shifts in the timing of migrations and life cycles are also occurring (Fischlin and Midgley, 2007). In the Arctic, the retreat of the sea ice is disrupting the habitats of major species such as the polar bear and other marine mammals (ACIA, 2004).

[32] Shifts in the range of species are actually causing the numerical biodiversity in some regions to increase (e.g., there are more different species now in the Arctic) in the short term, but this trend is expected to reverse as the climate continues to warm.

landscapes and ecosystems.[33] These effects can also have significant economic impacts, such as reduced storm surge protection from coastal wetlands and loss of valuable natural products used in foods and drugs. Thus, with the pace of climate change accelerating, the potential for significant disruption of wildlife and loss of biodiversity is quite possible and the impacts should be accounted for in risk analyses.

6. **Ocean acidification.** The response of marine species to changes in ocean chemistry[34] is unclear but fundamental.[35] If the CO_2 concentration continues to rise as projected, some calcifying marine organisms may not be able to adapt, making disruption and even extinction more probable (Monaco Declaration, 2009; Raven et. al., 2005). Projections are that surface waters will become corrosive to most coral by mid-century (Silverman et al., 2009). The need to understand the full consequences for the marine food chain urgently merits further research, but consequences could be significant as calcifying marine organisms provide many critical ecological services, including augmenting terrestrial food resources, coastal protection by coral reefs, cultural amenities, and others.

7. **Increasing health risks.** Both weather and climate influence the location and frequency of health impacts, both directly (extreme weather events) and indirectly[36] (alterations to ecosystems and disease transmission). The severity of future health impacts will be determined by changes in climate combined with adaptation measures and socioeconomic factors (e.g., wealth, distribution of income, status of the public health infrastructure, provision of medical care, and access to adequate nutrition, safe water, and sanitation). Climate change could exacerbate a variety of health-related issues, including heat-related mortality (Kosatsky, 2005), diarrheal diseases, and diseases affected by high concentrations of ozone[37] and by allergens (Ebi et al., 2008). Demographic trends (i.e., a larger and older U.S. population) will increase overall vulnerability and socioeconomic factors will influence vulnerability at the local level.

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[33] There is relatively limited understanding of the roles of the many species that make up particular ecosystems (plants, animals, soil organisms, etc.) and especially whether there are particular sets of species that might be considered critical to the ecosystem.

[34] The increased uptake of CO_2 by the oceans is reducing the pH of seawater, making it more acidic.

[35] Acidification is reducing the amount of available calcium carbonate, which is the construction material for skeletons and protective shells of many marine organisms. Early research indicates that there is a wide range of sensitivities to acidification, suggesting that the initial consequences will involve changes in the relative populations of different species in marine ecosystems.

[36] Indirect effects can influence the incidence and prevalence of water-, food-, and vector-borne diseases, malnutrition, and diseases associated with poor air and water quality.

[37] There is a growing body of evidence that ozone concentrations would be more likely to increase than decrease in the United States as a result of climate change, assuming that precursor emissions are held constant (U.S. EPA, 2009). An increase in ozone could cause or exacerbate heart and lung diseases and increase mortality (Patz et. al., 2005).

8. **Impacts on Indigenous Peoples and cultures.** Much more than most, Indigenous Peoples draw resources from and depend upon the outdoor environment. Faced with changes in the natural environment, they have traditionally relied on two responses, both of which are largely unavailable to them in modern times: relocation to follow the sources of traditional plant and animal species (which is often not possible due to restriction to tribal lands and barriers to resource migration) and sharing of resources (loss of traditional culture[38] could change these relationships). For these peoples, whether on islands, in high latitudes, or elsewhere, the threats of climate change and sea level rise are viewed as terribly disruptive—making an irreversible switch to a market culture with a very nebulous and incomplete safety net is viewed as cultural destruction. Such losses are difficult or even impossible to value monetarily.
9. **Risks to the economy and to national security.** Due to the strong interconnectedness of the global economy, the consequences of significant regional disruptions[39] are now felt around the world, particularly affecting the nations that are most vulnerable (whether due to economics, changing climate, or environmental stress). The United States typically experiences a price change in response to a disruption, but elsewhere the impacts can be much more significant, endangering local, regional, and even international security.

These represent the minimum likely impacts from past and future emissions, assuming unconstrained or weakly constrained emissions in the future. In general, these impacts are a direct response to the changes in climate and the rise in the CO_2 concentration. With sufficient research, it should be possible to develop estimates of the associated minimum economic costs. Refining the estimates, however, will remain problematic because of inherent limits in scientific knowledge concerning the climate system and of how society will develop (e.g., the pace of technological improvement and choices society will make in deriving its energy) and adapt to changes in the climate.

While these impacts might represent a minimum set, there are at least two key problems in using this information for the type of cost-benefit study done in the past. First, because of the inertia of the climate system, these impacts will only be avoided by very large policy actions, and the benefits of the policy will only be seen well in the future; therefore, even moderate discounting can make the level of policy required appear not to be cost effective,

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[38] Sharing all that was harvested or hunted became the social safety net of Indigenous society and culture. To the extent that climate change forces Indigenous Peoples away from their traditional food and clothing resources, the whole basis of cultural interrelationships changes and the long-lived lessons of how to co-exist within nature (i.e., the Indigenous knowledge that is the basis of so many of their customs) are lost or become irrelevant.

[39] Food and fiber production, generation of hydroelectric and other renewable energy, water resources, personal safety (in the face of extreme weather conditions), tourism and recreation, etc. are critically dependent on the climate and prevailing environmental conditions.

even if the likely impacts include socially unacceptable outcomes.[40] Second, being only a minimal set of impacts, there is significant potential for the actual impacts to be well above this minimum, especially because of the very real possibility that thresholds, tipping points, and surprises lie ahead. As Weitzman (2009) makes clear, even very low probabilities of very large impacts can significantly affect the conclusions that emerge from comparative analyses of costs and benefits. It is for this reason that an alternative approach such as risk management is likely to be much more appropriate for use in climate policy analyses, limiting the role of integrated assessment models to comparative evaluation of the suitability of alternative policy approaches aimed at meeting particular reduction goal.[41]

5. Conclusions

As the climate changes faster, as impacts become more evident, and as global emissions continue to grow, the global community is rapidly approaching a critical fork in the road. On one path lies ongoing accelerating warming, shifting precipitation bands, intensifying droughts, and sea level rise of a meter or more per century, to name only a few likely impacts. This path even poses significant risks of catastrophic events or surprises, as poorly known thresholds are crossed. Failure to reduce and ultimately stop emissions of greenhouse gases in a timely fashion leads down this path. While the costs of energy may only modestly increase, the losses due to the impacts on the environment and on many societies will bring significant costs. The costs could include relocation of cities and infrastructure along many low-lying coastlines, even in the United States, and could be significantly greater than the costs calculated by the current generation of cost-benefit analyses.

Along the second path, the rate of warming is reduced, leading to less significant shifts and intensification of storms, an eventual slowing of the rate and final extent of sea level rise, a reduction in the projected pace and ultimate number of species extinctions, and, if emissions controls are aggressive, a greatly reduced likelihood of catastrophic outcomes. This is the projected path if the world aggressively limits cumulative greenhouse emissions during the 21st century to essentially no more than the emissions that occurred over the 20th century (IPCC, 2007a).

Although there are uncertainties, the present state of knowledge, as exemplified in the recent IPCC assessment (IPCC, 2007a, 2007b), clearly distinguishes the two paths. Essentially, as Australian scientist Barrie Pittock (2007) has said; “Uncertainties are inevitable; risk is certain.” The science clearly demonstrates that global cooperation and participation starting in the near future will be required to avoid putting the world at risk of very severe climate disruption. Although some attempts at a cost-benefit analysis of this decision have been attempted (e.g., Stern, 2007) and may be insightful, they are, and will

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[40] See the paper by Ackerman et al. in this volume.
[41] See the paper by Yohe in this volume.

continue to be, fraught with uncertainties and value judgments that may be impossible to resolve. Indeed, if a government's decision is based on resolving such uncertainties [as the Climate Change Science Program of the United States seemed formulated to attempt (CCSP, 2003)], the decision to constrain emissions can never be taken.

To overcome the limitations of cost-benefit analyses, especially given the range of uncertainties and possible nonlinearities and surprises described in Sections 2 and 3, a risk-based approach seems more viable. Section 4 provides a starting baseline of impacts with the potential to underpin such risk-based analyses—the listed impacts are largely unavoidable, although adaptation may moderate their harshness. With the unprecedented speed of the changes in atmospheric composition caused by the burning of fossil fuels, the consequences could quite plausibly overwhelm the biosphere and human society. Therefore, it seems essential that implementation of policies to limit emissions not be delayed by requests for the impossible—namely, for precise and detailed cost-benefit analyses.

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WORKSHOP PROCEEDINGS

Assessing the Benefits of Avoided Climate Change: Cost-Benefit Analysis and Beyond

Social Vulnerability and Risk

Kristie L. Ebi
ESS, LLC and
IPCC Working Group II
Technical Support Unit

May 2010

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Social Vulnerability and Risk

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Abstract

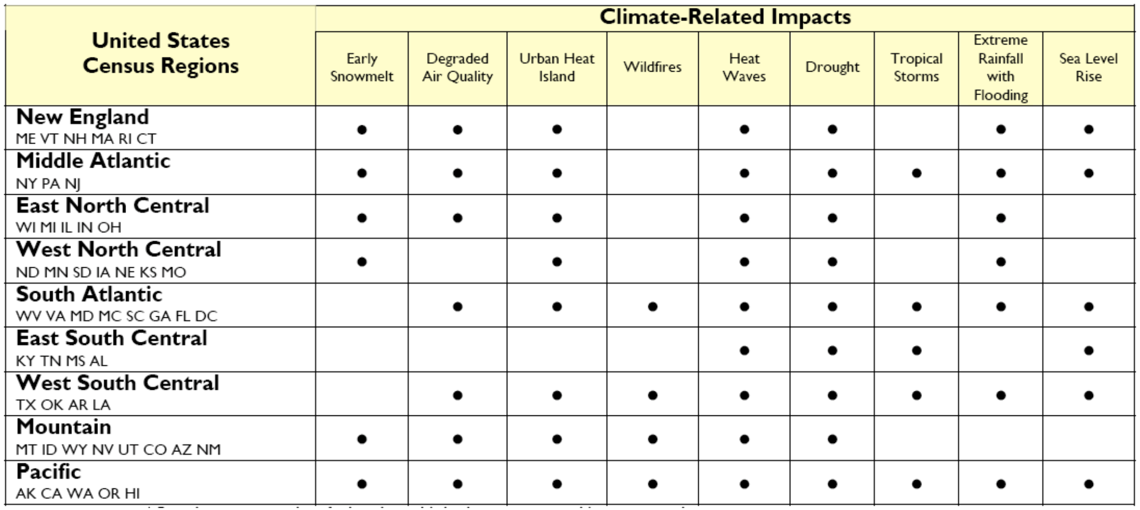
Climate change is affecting natural and human environments, with greater impacts projected as temperature and precipitation patterns continue to change. But what does evolving climate change mean to people in communities with different lifestyles and infrastructure, and thus, different ways of experiencing climate? Impacts will differ among communities because climate-related weather changes will be manifested differently and because communities have strengths and limitations in their response. Using national and state assessments hides local circumstances by averaging over these differences. Therefore, assessments of climate change risks based on aggregate analyses may provide a false sense of limited and manageable impacts when, in fact, some communities may suffer high consequences. For example, a prolonged future heat wave may bring reports of disparate impacts: some areas will see higher mortality rates, especially in elderly populations, and significant losses of livestock, while others may only notice a disruption in summertime sports, such as baseball.

Introduction

A recent assessment (SAP 4.3) concluded it is very likely that temperature increases, increasing carbon dioxide levels, and altered patterns of precipitation are already affecting U.S. water resources, agriculture, land resources, biodiversity, and human health (Backlund et al., 2008); similar conclusions were reached by the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007a). The SAP 4.3 also concluded that it is very likely that climate change will continue to have significant effects on these resources over the next few decades and beyond. For example, Table 1 summarizes some of the regional vulnerabilities to specific climatic changes[1] (Gamble et al., 2008). However, the extent of impacts depends not only on the magnitude and degree of climate change (i.e. the exposure to climate change), but also on the vulnerability of the affected population, system, or sector.

This paper examines ways in which climate change may affect communities differently, depending on vulnerabilities and types of impacts, and then illustrates this with a future scenario – the impacts of an intensified U.S. Midwestern heat wave in 2015 on three cities.

Table 1. Summary of Regional Vulnerabilities to Climate-Related Impacts
(*Source: Gamble et al,.(2008)*



United States Census Regions	Climate-Related Impacts								
	Early Snowmelt	Degraded Air Quality	Urban Heat Island	Wildfires	Heat Waves	Drought	Tropical Storms	Extreme Rainfall with Flooding	Sea Level Rise
New England ME VT NH MA RI CT	●	●	●		●	●		●	●
Middle Atlantic NY PA NJ	●	●	●		●	●	●	●	●
East North Central WI MI IL IN OH	●	●	●		●	●		●	
West North Central ND MN SD IA NE KS MO	●		●		●	●		●	
South Atlantic WV VA MD MC SC GA FL DC		●	●	●	●	●	●	●	●
East South Central KY TN MS AL					●	●	●		●
West South Central TX OK AR LA		●	●	●	●	●	●	●	●
Mountain MT ID WY NV UT CO AZ NM	●	●	●	●	●	●			
Pacific AK CA WA OR HI	●	●	●	●	●	●	●	●	●

Vulnerability, Sensitivity, and Risk

Vulnerability is the susceptibility to harm, which can be defined in terms of population or location. The IPCC defines vulnerability to climate change as the degree to which a system is susceptible to, or unable to cope with, the adverse effects of climate variability and change (IPCC, 2007b). Vulnerability to climate change is described as a function of the character, magnitude, and rate of climate variation to which a system is exposed, its

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[1] See the paper by MacCracken and Richardson in this volume for more detail.

sensitivity to that exposure, and its ability to avoid, prepare for, and effectively respond. When describing the vulnerability of a region, its characteristics, such as baseline climate, abundance of natural resources (e.g., access to freshwater), elevation, infrastructure, and other factors, can alter vulnerability. For example, coastal zones may be vulnerable to sea level rise or to typhoons. From a population perspective, vulnerability can be defined as the summation of all risk and protective factors that ultimately determine whether a subpopulation experiences adverse outcomes (Balbus and Malina, 2009).

Sensitivity can be defined as an individual's or subpopulation's increased responsiveness, primarily for biological reasons, to a particular exposure. Biological sensitivity may be related to developmental stage, pre-existing medical conditions, acquired factors (such as immunity), and genetic factors (Balbus and Malina, 2009). Socioeconomic factors also play a critical role in altering vulnerability and sensitivity, by interacting with biological factors that mediate risk (such as nutritional status) and/or lead to differences in the ability to adapt or respond to exposures or early phases of illness and injury. For example, adults who may be vulnerable during a heat wave include those over the age of 65, those with chronic diseases or taking certain medications, and other subpopulations. The proportion of these groups in a population is one determinant of a community's vulnerability. Table 2 lists groups particularly vulnerable to various climate-related exposures.

Table 2. Groups with Increased Vulnerability to Climate Change
(Source: Balbus and Malina, 2009)

Climate-Related Exposures	*Groups with Increased Vulnerability*
Heat stress	Elderly, chronic medical conditions, infants and children, pregnant women, urban and rural poor, outdoor workers
Extreme weather events	Poor, pregnant women, chronic medical conditions, mobility and cognitive constraints
Ozone (air pollution)	Children, pre-existing heart or lung disease, diabetes, athletes, outdoor workers

A climate-related *risk* is the result of the interaction of a physically defined hazard (i.e. floods and other extreme weather events, increasing temperature, and other factors) with the properties of the exposed system (its vulnerability) (Lim et al., 2005). Risk also can be considered as the combination of an event, its likelihood, and its consequences (risk = the probability of a climate hazard multiplied by a given system's vulnerability). Therefore, system vulnerability is a critical determinant of the risk the region or subpopulation faces when exposed to a particular hazard. For example, Cuba, which has extensive programs for reducing vulnerability to hurricanes, faces less risk than neighboring countries with less extensive disaster risk reduction programs (Thompson and Gaviria, 2004). This also means that programs to decrease vulnerability will, in most cases, decrease risk.

Aggregated vs. Differentiated Impacts

Human systems include social, economic, and institutional structures and processes. Climate is one of many influences on these systems; other influencing factors include access to financial resources, urbanization, and shifts in demographics. Climate change will interact with these factors to stress U.S. populations and societies, and in some instances, could push stressed systems beyond sustainable thresholds. Because sensitivity to climate and climate change varies across populations and societies, and across temporal scales, there is substantial variability in susceptibility and capacities to adapt. Aggregating impacts across this variability may hide unacceptable risks, thus providing a false sense of the extent of potential harm associated with climate change.

An example from Hurricane Katrina illustrates the problem with aggregation. In 2005, Hurricane Katrina caused more than 1,500 deaths along the Gulf Coast. Katrina caused damage in several states, but the vast majority occurred in Mississippi and Louisiana, primarily from storm surge in Mississippi and levee failure in New Orleans. As shown in Table 3, the damage from Katrina was only 0.69 percent of U.S. GDP, but 33 percent of GDP in the two states most affected, Mississippi and Louisiana.

Table 3. Economic Damage from Hurricane Katrina

Region	2005 GDP (2008 $US)	Hurricane Katrina Damage (2008 $US) = $86.3B
U.S.	$12,422B	0.69 percent of 2005 GDP
Mississippi & Louisiana	$263.5B	33 percent of 2005 GDP

NOTE: Damage figure does not include second-order effects, such as from disrupted oil and gas supplies.
Source: Bureau of Economic Analysis, US Dept. Commerce (http://www.bea.gov/).

Further, victims were not evenly distributed across the populations. Many victims were members of vulnerable populations, such as hospital and nursing-home patients, older adults who required care within their homes, and individuals with disabilities (U.S. CHSGA, 2006). According to the Louisiana Department of Health and Hospitals, more than 45 percent of the state's identified victims were 75 years of age or older; 69 percent were above age 60 (LDHH, 2006). In Mississippi, 67 percent of the victims whose deaths were directly, indirectly, or possibly related to Katrina were 55 years of age or older (MSDH, 2005).

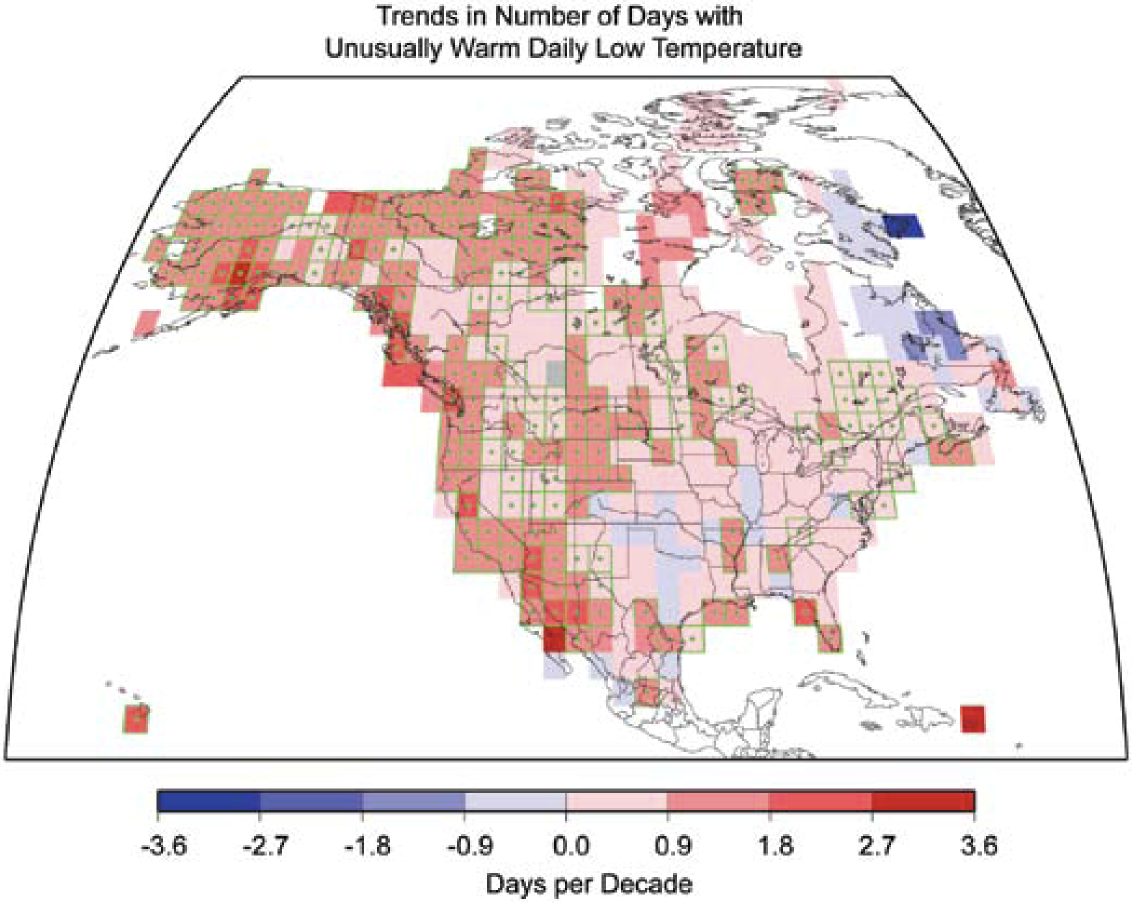
At hurricane evacuation centers in Louisiana, Mississippi, Arkansas, and Texas, chronic illness was the most commonly reported health problem, accounting for 33 percent (4,786) of 14,531 visits (CDC, 2006a). A quarter of the deaths indirectly related to the hurricane in Alabama were associated with preexisting cardiovascular disease (CDC, 2006b), and the storm prevented an estimated 100,000 diabetic evacuees across the region from obtaining appropriate care and medication (Cefalu et al., 2006). One study suggested that the hurricane had a negative effect on reproductive outcomes among pregnant women and infants, who experienced exposure to environmental toxins, limited access to safe food and water, psychological stress, and disrupted health care (Callaghan et al., 2007). Other vulnerable individuals included those without personal means of transportation and poor residents in Louisiana and Mississippi who were unable to evacuate in time (U.S. CHSGA, 2006).

Differential distributions of vulnerabilities and impacts need to be taken into account when planning programs to avoid, prepare for, and effectively respond to climate-related exposures. The costs and benefits of these programs can vary across populations and locations, depending on current activities, demographic structures, etc. For example, designing a heat wave early warning system for a particular location requires determining a threshold at which a heat wave is declared; this activity can be undertaken using various indicators of hot weather, but is basically similar across locations. The response activities will vary across populations depending on current activities and institutions. For example, once a heat wave is declared under the Philadelphia Hot Weather-Health Watch/Warning System, the city of Philadelphia and other agencies and organizations institute interventions that include encouraging friends, relatives, neighbors, and other volunteers ("buddies") to make daily visits to elderly persons during the hot weather (Kalkstein et al., 1996). These buddies are asked to ensure that the most susceptible individuals have sufficient fluids, proper ventilation, and other amenities to cope with the weather. This buddy system was built on an existing program to reduce rates of crime in at-risk neighborhoods. Such programs do not exist in many cities, so although it is an apparently effective model, different approaches may be needed when designing heat wave responses.

Case Study: Midwestern Heat Waves

Since 1950, the annual percentages of days exceeding the 90th, 95th, and 97.5th percentile thresholds for both maximum (hottest daytime highs) and minimum (warmest nighttime lows) temperature have increased when averaged over all of North America (Karl et al., 2008). The changes were greatest in the 90th percentile, increasing from about 10 percent of the days to about 13 percent for maximum and almost 15 percent for minimum. These changes decreased as the threshold temperatures increased, indicating more rare events. The 97.5th percentile increased from about 3 percent of the days to 4 percent for maximum and 5 percent for minimum. There were important regional differences in the changes, as shown in Figure 1. The largest increases in the 90th percentile threshold temperature occurred in the western part of the continent, while some areas, such as eastern Canada, show declines of as many as ten days per year from 1950 to 2004. Since the record hot year of 1998, six of the past ten years (1998-2007) experienced annual average temperatures that fall in the hottest 10 percent of all years on record for the U.S. (Karl et al. 2008).

Figure 1: Trends in Number of Days with Unusually Warm Daily Low Temperatures
(Source: Karl et al., 2008)



Note: Trends in the number of days in a year when the daily low is unusually warm (i.e. in the top 10 percent of warm nights for the 1950-2004 period). Grid boxes with green squares are statistically significant at the p=0.05 level (Peterson et al., 2008). A trend of 1.8 days/decade translates to a trend of 9.9 days over the entire 55-year (1950-2004) period, meaning that ten days more a year will have unusually warm nights.

Heat waves are the leading cause of weather-related mortality in the United States (CDC). Over the period 1979–1999, 8,015 deaths in the United States were heat-related, 3,829 of which were due to weather conditions (Donoghue et al., 2003). As with other extreme events, the risk of heat waves is not evenly distributed. Populations in the Midwest have an increased risk for illness and death during heat waves, as evidenced during events occurring in the 1980s and 1990s. A heat wave in July 1980 caused a 57 percent increase in mortality in St. Louis and a 64 percent increase in Kansas City (Jones et al., 1982). The 1995 Chicago heat wave is perhaps the most widely known; it caused an estimated 696 excess deaths (Semenza et al., 1996; Whitman et al., 1997). A heat wave of similar magnitude in 1999 resulted in 119 deaths in Chicago (Palecki et al., 2001).

An analysis of future heat wave risk in the Midwest found that in coming decades, heat waves in the Midwest are likely to become more frequent, longer, and hotter than cities in the region have experienced in the past (Ebi and Meehl, 2007). This trend will result from a combination of general warming, which will raise temperatures more frequently above thresholds to which people have adapted, and more frequent and intense weather patterns that produce heat waves. Studies projecting future mortality from heat foresee a substantial increase in health risks from heat waves. Several factors contribute to increasing risk in Midwestern cities, including demographic shifts to more vulnerable populations and a built infrastructure originally designed to withstand the less severe heat extremes of the past. The elderly living in inner cities are particularly vulnerable to stronger heat waves; other groups, including children and the infirmed, are vulnerable as well. Adaptations of infrastructure and public health systems will be required to cope with increased heat stress in a warmer climate.

Throughout much of the Midwest, projections for 2090 (compared to 1975) forecast increases in nighttime minimum temperatures of more than 2 °C (3.6 °F) during the worst heat waves. Nighttime temperatures are important in determining the extent of health impacts during a heat wave, as limited nighttime cooling is associated with higher mortality (Kovats and Hajat, 2008). Table 4 summarizes projections of increases in heat wave frequency and intensity in Chicago, Cincinnati, and St. Louis in 2090 (Ebi and Meehl, 2007). These projections are well above present-day observations (i.e. more and longer-lived heat waves). On average, the frequency of heat waves for all three cities increased by 36 percent and the duration of individual heat waves increased by 27 percent. Combining these two effects implies an overall increase of about 70 percent in the annual number of heat wave days for the Midwestern region by the late 21st century. Moreover, as shown in Table 4, these extreme days will be hotter on average than at present.

Applying the magnitude of the 2003 European heat wave to five major U.S. cities (Detroit; New York; Philadelphia; St. Louis; and Washington, D.C.), Kalkstein et al. (2008) concluded that a heat wave of the same magnitude could increase excess heat-related deaths by more

Table 4. Projected Increases in Heat Wave Frequency and Duration in 2090 for Chicago, Cincinnati, and St. Louis *(Source: Ebi and Meehl, 2007)*

City	***Temperature Increase***	***Frequency Increase (Heat waves per Year)***	***Duration Increase (Days per Year)***
Chicago	4.0°F	24 percent	21 percent
		From 1.7 to 2.1	From 7.3 to 8.8
Cincinnati	4.3°F	50 percent	22 percent
		From 1.4 to 2.1	From 8.8 to 10.7
St. Louis	4.7°F	36 percent	38 percent
		From 1.4 to 1.9	From 10.3 to 14.2

Note: The table shows ensemble-average projections for each city. Because these are averages, they describe a typical summer in the late 21st *century, not what an extreme year would look like.*

than five times the average. New York City's total projected excess deaths exceeded the current national summer average for heat-related mortality, with the death rate approaching annual mortality rates for common causes of death, such as accidents.

Conclusions

The risk of adverse impacts due to climate change depends on exposure to a particular climatic event, its likelihood, and the consequences. The consequences of exposure depend on the geographic and socioeconomic vulnerability of the affected region and sector. Exposures and vulnerability vary over temporal and spatial scales, resulting in highly variable patterns of possible impacts. Aggregating over this variability can produce misleading assessments of the extent and magnitude of possible impacts. Societies will need to prepare for not just the average impacts, but for the tails of the distribution. A small or moderate average impact for a state or the nation can hide unacceptable impacts to some sectors and regions, with some populations experiencing limited adverse consequences, while others experience devastating impacts.

Illustration: News of 2015 Midwest Heat Wave

The societal impacts of model projections of the future can be difficult to imagine, particularly when dealing with changes in changes in events that are infrequent. For example, what does it mean for the population of Chicago to experience a given increase in the number of heat wave days per year? What strains would be placed on social systems and public health services?

To help make future events easier to visualize, we have created fictional news accounts based on projections of future heat wave occurrence in the U.S. Midwest. Our intent is not to create worst-case or nightmare scenarios such as those played out in popular movies, but rather to illustrate in a familiar format the impacts of the kinds of changes that can be reasonably expected based on current projections.

The scenario we have chosen is a prolonged heat wave in 2015 affecting the Midwest, including Cincinnati, Chicago, and St. Louis. We chose a year in the near future in order to make this fictional world easier to relate to than the more distant future and in order to examine the effects such a heat wave can have on an infrastructure that is no better adapted to climate extremes than today's.

We include a fictional story in the future *New York Times* as an overview of the scenario , a business story in the *Des Moines Register*, and a sports page story in the *Cincinnati Enquirer* as an illustration of the unexpected effects of climatic changes on particular sectors. References to climate trends are drawn from the references in this chapter, and references to events prior to 2009, such as prior heat waves, refer to actual events. We have based quantitative measures such as temperatures and economic damages, where possible, on estimates in the peer-reviewed literature (Ebi and Meehl, 2007 and references therein, St. Pierre 2003), published conference proceedings (Gaughan, 2009), and news accounts of past heat waves. Names of people are fictional.

Acknowledgement

The author thanks science writer Erika Engelhaupt for penning the fictional news stories.

The New York Times August 10, 2015

Midwest Heat Wave Drags On, Death Reports Climb

By ERIKA ENGLEHAUPT

The heat wave that has scorched the Midwest continued to cause widespread problems yesterday, including more heat-related deaths and widespread power grid failures as air conditioners strained across the region.

The heat wave has ended its fourth consecutive week with temperatures regularly topping 100 degrees in many cities, making it the most widespread and intense heat wave on record for the Midwest, government scientists reported yesterday. The experts said that because the heat wave got an early start this year, it could set an additional record for the longest heat wave in U.S. history if conditions continue.

“Chicago looks more like Atlanta this year,” John Carlo, senior scientist at the National Climatic Data Center in Asheville, N.C., said in announcing the latest temperature data at a briefing in Washington.

Other scientists pointed out the unusual conditions that have led to the heat wave. Domes of high atmospheric pressure have been getting larger in recent years, and this summer’s high pressure event is keeping temperatures high both during the day and at night. Average temperatures in Cincinnati have been 8°F above normal for July, with nighttime temperatures at least 10°F higher than normal.

Temperatures have reached heat wave status in at least 15 states stretching from Texas in the south to Iowa in the north, and from Colorado to parts of the East Coast.

“Ten years ago, we were publishing model results showing that these atmospheric features would lead to more and longer heat waves,” Mr. Carlo said. “But our models were for the middle of the century. This could be an early indication of formerly extreme conditions that are becoming more normal.”

At least 4000 deaths have now been attributed to the heat wave, but officials say that number may rise significantly as a backlog of death certificates is issued. A survey of morgues in St. Louis found that more than 2500 excess deaths have occurred during the heat wave in that city alone. Most of these deaths are assumed to be related to the heat, with elderly people highest among the mortalities.

Morgues have been struggling to find places to store the bodies. In Cincinnati, the county coroner’s office converted air-conditioned trailers to makeshift morgues only to have the electrical power fail yesterday afternoon, forcing the office to run the air conditioners on backup generators.

“We have been seeing a very high number of patients with cardiopulmonary problems,” said Dr. John Wilkinson of Cincinnati General Hospital.

“I just don’t feel good. I’m exhausted,” said May Hopkins, 91, as she fanned herself on her front porch in west Cincinnati. Her neighborhood has few shade trees to help cool her house. Ms. Hopkins said she knows no one who can check on her during the day except the local Meals on Wheels program, which has found itself operating as a makeshift emergency service for the elderly and homebound.

A four-day blackout affected large parts of 5 states, caused by massive demands on the electrical grid coupled with damaging winds, hail, and lightning from thunderstorms. The lack of air conditioning and electric fans meant no relief from nighttime heat for many and may have raised the death toll.

Cincinnati Enquirer July 15, 2015

Braves Blast Reds in Heat Wave Meltdown

By ERIKA ENGLEHAUPT

Baseball officials are calling for new rules to help teams beat the heat after the Reds' disappointing 5-1 and 4-2 doubleheader losses to the Atlanta Braves yesterday.

The teams faced off in a sweltering series after a highly unusual postponement due to heat the previous afternoon. In the middle of a record-setting heat wave, temperatures in Cincinnati exceeded 100 degrees for three days prior to Thursday's game and did not dip below 80 degrees at night.

Last week, the Major League Baseball All-Star Game scheduled at Busch Stadium in St. Louis was cancelled because of high heat.

"Some teams have asked for a temperature threshold for starting a game, and we will consider that option," said baseball commissioner John Dupree after a string of slow-selling games. Umpires can call, suspend, or resume a game based on weather, but how hot is too hot is up to their judgment.

League officials say teams in the majors should play more twilight doubleheaders, with games starting after the worst afternoon heat is over. But owners say these games, which in the minor leagues typically allow fans to watch two games for the price of one ticket, would lose too much money for Major League Baseball.

The Reds played for a near-record low crowd of 13,450 yesterday. Many fans complained and began leaving the ball park after beverages ran out.

"We're just glad we don't have artificial turf; that gets really hot," said Victor Fuentes, who was 3-for-6 with two doubles. Fuentes spoke to reporters after the game with a towel draped around his neck dripping with cold water and ammonia to keep cool.

During a 1999 heat wave, a thermometer on the artificial turf at the old Cinergy Field just before the opening pitch registered 154 degrees. Today's temperature on the grass field at Great American Ball Park ticked up to 103 degrees, compared to 99 as the day's official local high.

Des Moines Register August 18, 2015

Heat Takes Toll on Animals and Farm Economy

By ERIKA ENGLEHAUPT

Tom Williams of Pottawattamie County looked across his feedlot last week to find his cattle panting with their tongues hanging out, many lying listlessly on the ground. Some were dead. All told, Williams lost nearly 200 of his 2,500 head.

"I've never seen anything like it, and I've been doing this all my life," Williams said. The biggest loss is not from the deaths, he said, but from lost production of animals that did not gain weight during the hot spell. The cost of a dead steer may be $500 to $600, but Williams estimates he could lose that much from 35 to 40 survivors having eaten too little to reach market weight. Williams said he is not insured for this kind of loss.

Farmers throughout the region are reporting the deaths of thousands of swine, poultry, and cattle. Dairy production is also down by about half, according to the Iowa Department of Agriculture.

This year's heat wave has set records for temperature and agricultural losses. Early government estimates of national agricultural losses top $75 billion, compared to $64 billion for the 1988 heat wave that ravaged the Great Plains.

Past heat waves also killed or damaged livestock production, although this year's losses are on track to surpass all records. A heat wave in 1995 cost the cattle industry more than $28 million in animal deaths and decreased performance. In 1999, a heat wave in Nebraska led to more than 3,000 cattle deaths and $20 million in economic losses.

Animals usually seek shade and rest when their temperatures rise, said Joseph McCoy, a large animal veterinarian in Omaha. But all livestock can experience heat stress when high temperatures last for several days or more, and hot nighttime temperatures are especially damaging because animals cannot recover from the daytime heat. McCoy said feedlot managerscan install water sprinklers, provide shade, and avoid transporting cattle during extreme heat.

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Background Papers for Session 3:

The Role of Uncertainty in Assessing the Benefits of Climate Policy

WORKSHOP PROCEEDINGS

Assessing the Benefits of Avoided Climate Change: Cost-Benefit Analysis and Beyond

Representation of Climate Impacts in Integrated Assessment Models

Michael D. Mastrandrea
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May 2010

PEW CENTER ON Global CLIMATE CHANGE

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The complete workshop proceedings, including video of 17 expert presentations, this summary report, and individual off-prints of expert papers are available free of charge from the Pew Center on Global Climate Change at http://www.pewclimate.org/events/2009/benefitsworkshop.

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Representation of Climate Impacts in Integrated Assessment Models

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Abstract

Integrated Assessment Models (IAMs) of climate change are broadly employed to examine alternative climate policy scenarios. Policy evaluation models quantify the consequences of specific scenarios in terms of a suite of environmental, economic, and social performance measures. Policy optimization models calculate the "best" scenario that optimizes a single performance measure, and are often used for formal cost-benefit analysis (CBA) of climate mitigation policies. IAMs, by necessity, incorporate simplified representations of climate impacts. This paper provides a brief overview of IAMs and an examination of the modeling of climate impacts in prominent IAMs employed for CBA. Over time, these representations are updated by model developers to reflect advancing research, but they generally lag behind current scientific understanding of climate impacts. Moreover, IAMs employed for CBA require translation of economic and non-economic impacts into monetary damages, a key source of uncertainty to which model results are sensitive. Explicit incorporation of non-market impacts, new categories of impacts identified in the scientific literature, and uncertainty in the severity of climate impacts generally will increase climate damages in IAMs and the stringency of recommended emissions reductions.

Introduction

Integrated Assessment Models (IAMs) of climate change combine natural and social scientific information to examine the key interactions between the climate system and society. Their primary purpose is to inform policy decisions on climate mitigation (greenhouse gas emissions reduction). IAMs couple simplified representations of relevant systems to model climate change, its impacts, and the costs of policy measures to reduce those impacts. Those models that attempt to translate climate impacts into monetary damages are often used for social cost of carbon calculations (monetary estimates of the benefit of cutting one ton of carbon emissions today) and cost-benefit analyses (CBAs) to determine "optimal" policy. The purpose of this short paper is to provide a brief overview of IAMs and an examination of the modeling of climate impacts in IAMs employed for CBA. A more detailed scholarly review of IAMs is provided by Goodess et al. (2003).

Categories of IAMs

Existing IAMs reflect a range of modeling approaches to provide policy-relevant information, and most can be summarized by two general categories: policy optimization and policy evaluation. IAMs of all types must make choices about how to account for critical uncertainties in climate and social systems and their interactions. Different assumptions about these parameters create significantly different modeled outcomes and associated policy implications.

Policy Optimization

Policy optimization models are designed to calculate the "best" trajectory for future emission reductions based on a specific performance measure, such as minimizing the sum of mitigation costs and monetized damages from climate impacts.[1] The complexity of optimization models is limited by the numerical algorithms required in optimization calculations. Climate and economic systems are generally represented by a small number of equations, with a limited number of geographic regions (~1-16). Fundamental aspects of the policy optimization framework and its applicability to climate policy have been heavily critiqued, such as intergenerational discounting, economic valuation of non-market climate change damages, and the fact that "optimal" solutions based on a host of uncertain parameters can change significantly when key parameter values are varied (e.g., Mastrandrea and Schneider, 2004). See Ackerman et al. (this volume) for further discussion of such critical issues.

Policy optimization models are used in two main applications. In CBAs, the preferences of climate policymakers are represented by a mathematical "utility function" for social welfare, generally expressed in terms of economic wealth, which is then maximized. In

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[1] In this case, increasing investment in mitigation reduces future climate change and related damages, and the model calculates an "optimal" balance between the two.

cost-effectiveness analyses, the optimization is subject to a constraint, such as avoiding a specific level of global temperature increase. Examples of policy optimization models include DICE/RICE (Nordhaus and Boyer, 2000; Nordhaus, 2008), FUND (Tol, 2002; Tol, 2005), PAGE (Hope, 2006; Hope, 2009), and MERGE (Manne et al., 1995).

Policy Evaluation

Policy evaluation models are designed to calculate the consequences of specific climate policy strategies in terms of a suite of environmental, economic, and social performance measures. These models are not subject to the constraints of optimization models, and therefore can incorporate greater complexity in their representations of natural and social processes and regional detail. Thus, they are generally applied to comparisons of the consequences (e.g., regional economic and environmental impacts) of alternative emissions scenarios. Examples of policy evaluation models include AIM (Kainuma et al., 2002), MESSAGE (Messner and Strubegger, 1995), IMAGE (Alcamo et al., 1998), and the new CIAS (Warren et al., 2008). Some policy optimization models (e.g., DICE/RICE, FUND, PAGE) are also applied to evaluation (e.g., CBAs) of specific scenarios, but their relative lack of complexity and geographic resolution limits the range of questions they can address.

Treatment of Uncertainty

As mentioned above, model results are highly sensitive to critical uncertainties in climate and social systems and their interactions, and different IAMs take different approaches to incorporating uncertainty (see the paper by Hope in this volume for more information on parameter uncertainty). *Deterministic analyses* employ “best-guess” (or expected) values for all model parameters (e.g., parameters determining the sensitivity of the climate to increasing greenhouse gas concentrations, the translation of climate impacts into monetary terms, and the costs of emission reductions). The effect of alternative parameter choices on model outputs and the importance of uncertainty in specific parameters can be determined through sensitivity analyses, which examine differences in model outputs across runs varying a specific parameter in order to quantify the sensitivity of model results to changes in that parameter (e.g., Nordhaus, 2008). *Probabilistic analyses* specify probability distributions for some or all uncertain model parameters, resulting in probability distributions for model outputs (e.g., Hope 2006 and this volume; Warren 2008). *Adaptive or hedging analyses* combine aspects of the two to examine implications of future learning about key scientific and policy uncertainties, such as calculating near-term strategies given current uncertainties, but with specific assumptions about the resolution of those uncertainties in the future (O’Neill, 2008).

IAMs and Climate Impacts in CBA

This paper focuses on how simple IAMs in CBA estimate damages from climate change impacts. Deterministic policy optimization models have primarily been used in CBAs to date. The optimal solutions for these models generally suggest implementing low levels of climate policy controls, which gradually increase over time, but are much less stringent than current policy proposals. These solutions allow significant continued increases in atmospheric greenhouse gas concentrations and temperature. For example, the optimal solution of the most recent version of the DICE model, DICE-2007 (Nordhaus, 2008), allows increasing global carbon emissions throughout the 21st century, increasing from 7.4 GtC/year (Gigatons of carbon per year) in 2005 to 11.3 GtC/year in 2105. These emissions are 16 percent below baseline (no policy) emissions calculated by the model by 2025, 26 percent below baseline by 2050, and 43 percent below by 2105 (but again, all above current emissions levels). Atmospheric CO_2 concentrations reach 586 ppm (not including other greenhouse gases) by the end of the century, compared to 686 ppm in the baseline scenario.

An exception is the probabilistic model PAGE, which was also applied recently in an optimization analysis (Hope, 2008; for more information see the paper by Hope in this volume). Global carbon emissions initially increase from 7.7 GtC/year in 2000, peak in 2010 at 11 GtC, and decrease significantly thereafter, particularly in the second half of the century. Annual carbon emissions roughly return to 2000 levels (8 GtC) by 2050, and are 88 percent lower than 2000 levels (0.9 GtC) by the end of the century. These emissions are 15 percent below baseline emissions in 2020, 60 percent below in 2060, and 93 percent below at the end of the century. Atmospheric CO_2 concentrations are 495-597 ppm by the end of the century (including other greenhouse gases in CO_2 equivalent units), compared to 638-792 ppm in the baseline scenario.[2]

These two optimal solutions differ markedly in annual emissions, particularly in the second half of the century. Figure 1 displays annual carbon emissions for the two models' optimal solutions and baseline scenarios (which also differ). A broader discussion of the reasons for large variations in "optimal" outcomes for emissions reductions (e.g., discounting choices) can be found in Ackerman et al. (this volume).[3] One key determinant, however, is the differing representation of climate impacts in these IAMs. As described above, IAMs by necessity employ simplified and incomplete representations of climate change and resulting climate impacts. MacCracken (this volume) presents a detailed discussion of the general challenges of estimating the environmental and social impacts of climate change in monetary terms, a topic also addressed by Ackerman et al. and Yohe in this volume. Here, the focus is an overview of how climate impacts are represented in particular IAMs employed for CBA. The following section briefly examines the categories of impacts

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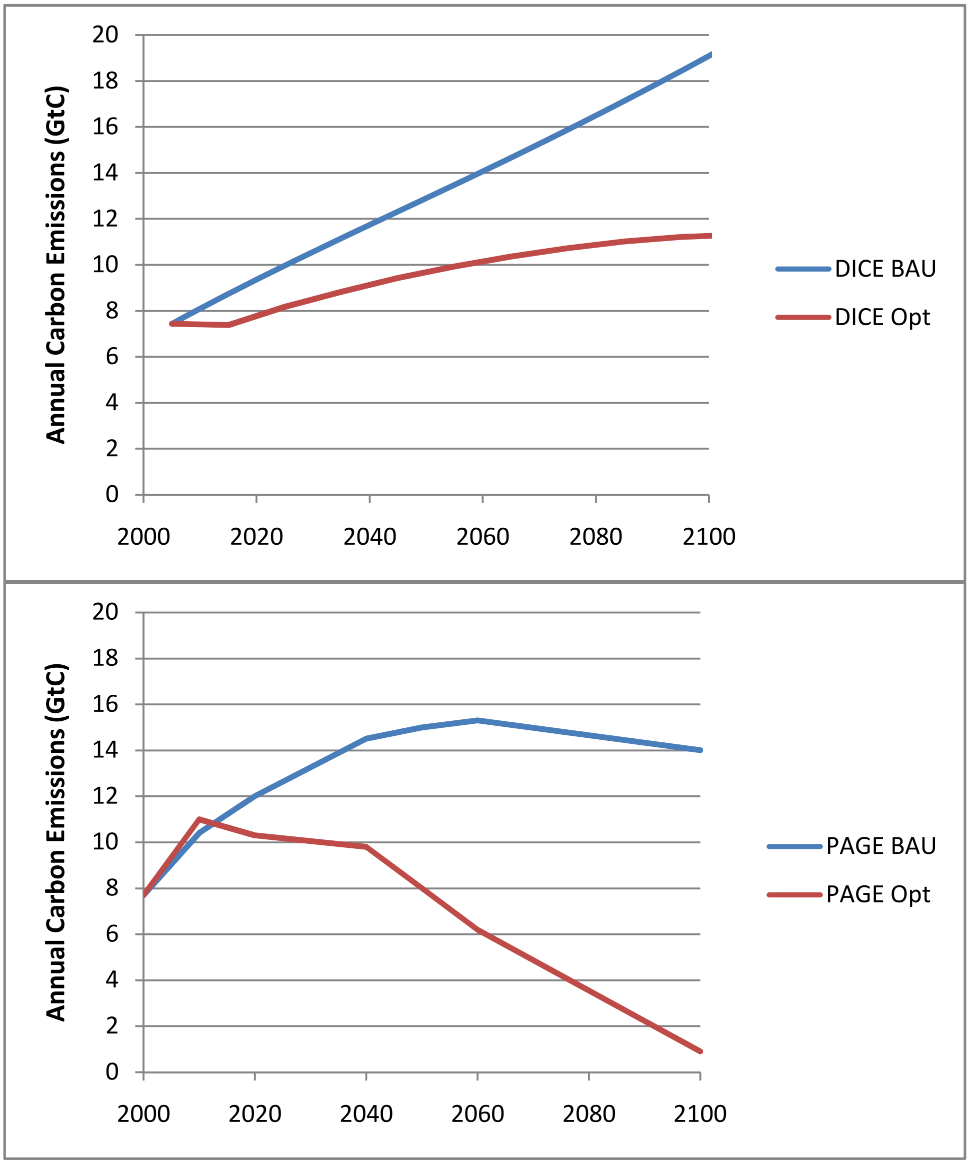
[2] These concentrations are ranges because of the probabilistic structure of PAGE.

[3] "Optimal" solutions are particularly sensitive to the choice of discount rate, as in general, large magnitudes of climate impacts accumulate farther in the future, while costs of emissions reductions to avoid those impacts are incurred earlier. "Optimal" solutions under lower rates of discounting are significantly more stringent (e.g., Nordhaus, 2008; Hope, 2009).

incorporated in three prominent optimizing IAMs: DICE, FUND, and PAGE. A more detailed discussion of impacts in versions of these models can be found in Warren et al. (2006).

Figure 1. Comparison of DICE and PAGE baseline scenarios and optimal solutions. The optimal solutions differ significantly, in part due to differences in the representation of climate impacts between the two models. See Ackerman et al. (this volume) for a broader discussion of the reasons for such differences.



Unpacking Impacts in IAMs

Climate change in IAMs is generally represented by an increase of global or regional average temperature as a proxy for the full range of changes to the climate system. Impacts are quantified through one or more *climate damage functions* for each model region. These damage functions provide monetary estimates of climate impacts associated with different levels of temperature increase, often expressed in terms of percentage loss of GDP. Functions are either specified for specific market and non-market sectors or for aggregate damages across sectors. In general, damages are assumed to rise nonlinearly with increasing temperature—each additional degree of temperature rise leads to a greater increase in damages. However, different models assume different curvature and steepness of the rising damage function.

FUND includes sector and region-specific impact functions for agriculture, forestry, water resources, energy consumption, sea level rise, ecosystems, and health (split into functions for diarrhea, vector-borne diseases, and cardiovascular and respiratory illnesses affected by heat and cold). These functions are described in FUND's technical description (Anthoff and Tol, 2008).

DICE uses a single global aggregate damage function based on impact estimates for a similar list of sectors: agriculture, other market sectors (e.g., energy, water, forestry), coastal vulnerability, health, non-market impacts (e.g., outdoor recreation), human settlements, and ecosystems. DICE also includes damages from potential abrupt climate changes such as the shutdown of ocean currents, large-scale melting of ice sheets, or release of methane from permafrost. These damage functions are derived from a climate impact analysis most completely described by Nordhaus and Boyer (2000), Chapter 4.

PAGE2002 simulates region-specific aggregate economic and non-economic damages, as well as damages from abrupt climate changes (discontinuities). Total economic and non-economic damages are calibrated to be consistent with impact estimates summarized in the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report, including estimates by Tol (1999) and Nordhaus and Boyer (2000) that inform the damage estimates in DICE and FUND. Impacts in PAGE2002 are described in Hope (2006). Among optimizing IAMs, only PAGE explicitly incorporates uncertainty in impact estimates through probability distributions for the parameters of its climate damage functions (Hope, this volume), although implementation of a probabilistic damage function has also been explored in DICE (Mastrandrea and Schneider, 2004), as have the implications of uncertainty in sectoral climate damages in FUND (Tol, 2005).

Damage estimates in these models are often based on studies from one country or region, since similar studies do not exist for other regions of the world. Market and non-market damages in DICE are based on studies of impacts on the United States that are then scaled up or down for application to other regions. Many of the estimates to which market damages in PAGE are calibrated are also based on an extrapolation of studies of the U.S. Only FUND uses regional and sector-specific estimates. However, in some sectors these estimates also originate in one country, or may be dominated by estimates from one region—for example in the energy sector, (the sector which accounts for most of the economic damages in FUND, see below) estimates for the UK are scaled across the world.

The treatment of other aspects of climate impacts also varies among models. For example, only FUND's damage functions take into account the rate of temperature change as well as its magnitude, and only for the agricultural and ecosystem sectors. Only PAGE incorporates a potentially significant contribution from non-market damages to overall damage estimates. Models also have various ways of simulating damage due to abrupt climate changes, but all are necessarily simplistic. DICE includes these damages in its aggregate function, while PAGE represents them as a separate (uncertain) source of damages that increase in likelihood after temperature crosses an uncertain threshold. FUND does not include impacts from abrupt climate changes in its default damage estimates, although it has been used to examine estimates of damages from specific abrupt climate changes, such as shutdown of the North Atlantic thermohaline circulation (Link and Tol, 2006).

Global Damage Functions

Figure 2 displays global damage estimates from recent versions of these three IAMs: DICE-2007, FUND2.9, and PAGE2002, respectively. Panels a and c represent damages in terms of percentage loss of global GDP (with losses as positive values) as a function of global temperature increase above preindustrial levels. In Panel c, from PAGE2002, the probabilistic structure of the model generates a range of relationships between temperature and damages, which are displayed separately for economic, non-economic, and discontinuity damages. Panel b, from FUND2.9, represents losses as negative values (the opposite of the other two Panels), as a function of temperature increase above 1990 levels (~0.6°C higher than the preindustrial level). Note that damage estimates expressed in terms of percent loss of GDP are dependent on the chosen GDP growth scenario, which varies among models. Panel b displays damage functions based on several growth scenarios consistent with storylines from four IPCC Special Report on Emissions Scenarios (SRES). For comparison, GDP growth rates in PAGE2002 are those of the SRES A2 scenario, and GDP growth is determined endogenously in the DICE-2007 model.[4]

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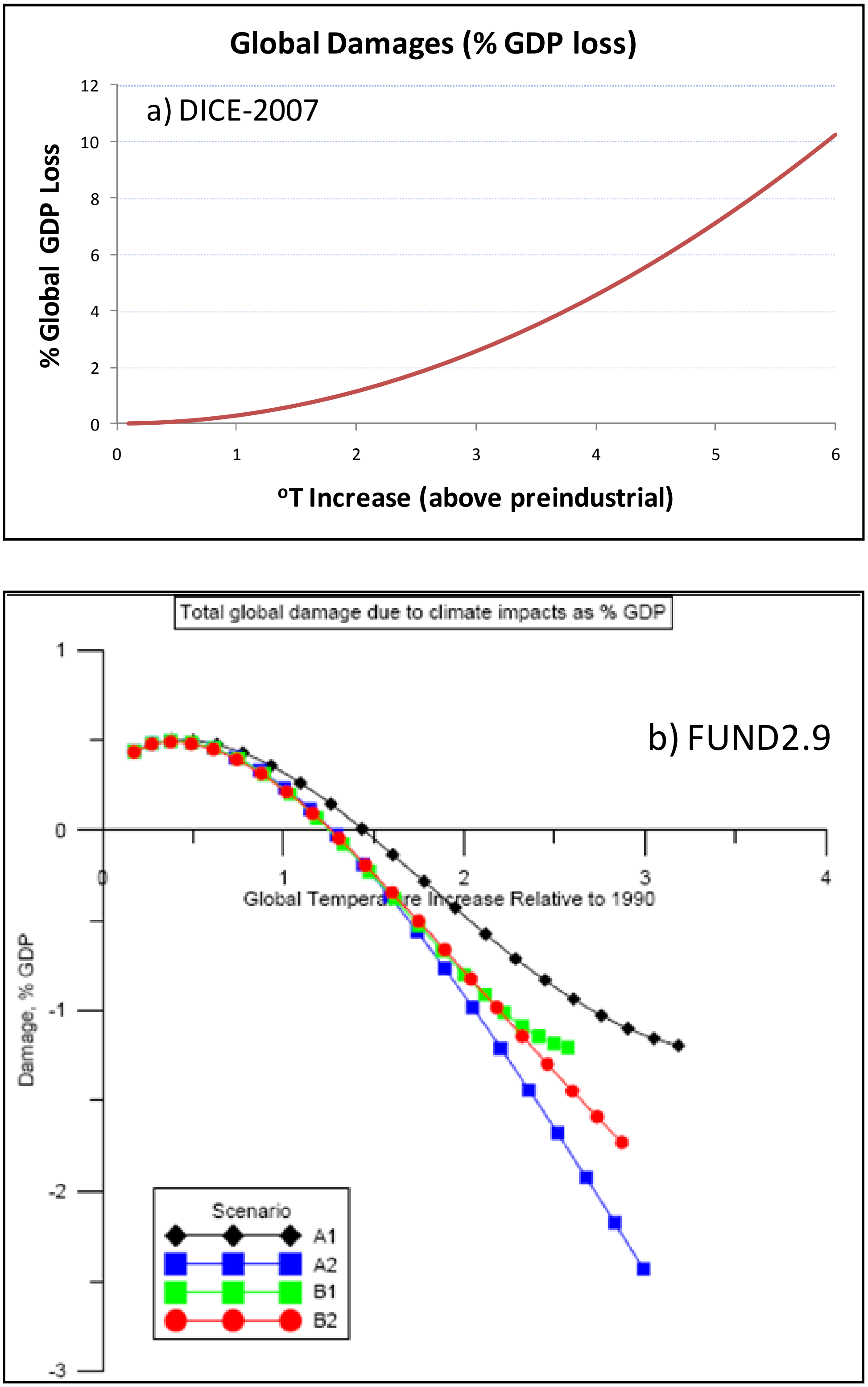
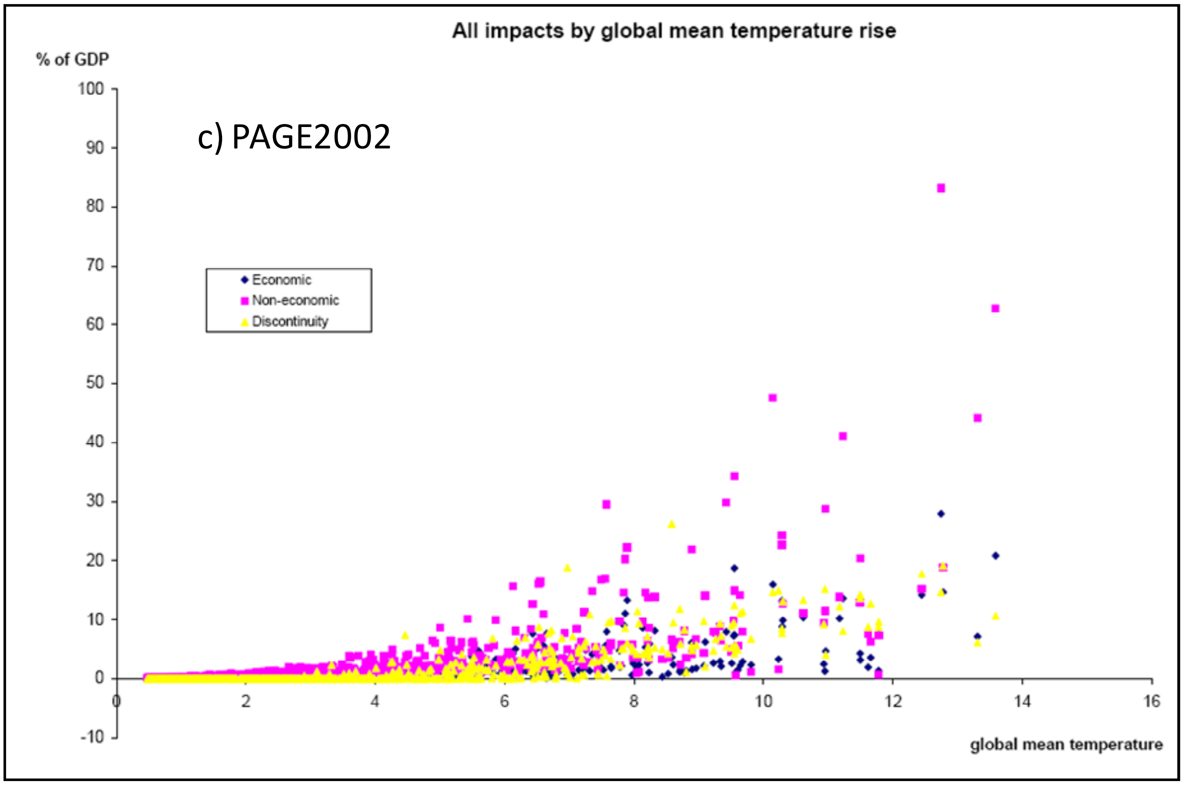
[4] Global GDP growth rates are also affected by the choice of aggregation across regions—generally using either market exchange rates (MERs) or purchasing power parity (PPP) calculations. Choice of aggregation method varies across models, though most recent models use PPP. Aggregation across regions also involves implicit or explicit equity weighting. See papers by Ackerman, et al. and Ebi in this volume for further discussion.

Figure 2. Global damage estimates in terms of percentage loss of global gross domestic product (percent GDP) as a function of global average temperature increase, for a) DICE-2007, b) FUND2.9, and c) PAGE2002.





Although the panels of Figure 2 do not represent a perfectly analogous comparison, it is clear that the relationship between temperature increase and climate damages varies among IAMs. In FUND, aggregate damages are a net positive (i.e. economically beneficial) for the first 1-1.5°C of temperature increase above 1990 levels. Initial positive impacts primarily arise in the health sector, where reduced cold-related deaths and illnesses outweigh negative health impacts through ~3°C of warming, and the energy sector, where impacts are initially positive for the first 1°C of warming due to reduced heating needs. However, impacts from the energy sector then sharply decrease and become the largest contribution to negative impacts at higher levels of warming, due to increased air conditioning needs. In DICE, impacts are always negative, increasing nonlinearly as temperature increases, and estimates are higher than those found in FUND. In this application, the DICE-2007 damage function has been increased (higher damages at a given level of temperature increase) compared to previous versions of the model. The primary differences include a recalibration of the costs of catastrophic damages, refining estimates for regions with large temperature increase, and revision upward of overall damages at low levels of temperature increase that previously were assumed to provide a small but positive net benefit (Nordhaus, 2008). PAGE2002's probabilistic results indicate that damages from market and non-market sectors, as well as abrupt climate change are of similar magnitude, and in total are somewhat higher than DICE damages, with the possibility of much higher estimates (those estimates, particularly for non-market impacts, spreading above the main clustering in Figure 1c).

Consistency of IAM Damage Functions with Current Science

Estimates of climate impacts in economic terms necessarily lag behind the scientific impacts research on which they are based. The core impact estimates of these IAMs are based on literature from 2000 and earlier. Since that time, scientific understanding of climate impacts has advanced, leading to, in general, the association of greater risks with smaller temperature increases (see, e.g., Smith et al., 2009).

For example, there is now higher confidence in projections of increases in the occurrence of extreme events (e.g., droughts, heat waves and floods) as well as their adverse impacts (Core Writing Team et al., 2007). More recent studies have also estimated potential economic damages from increased extreme weather events (e.g., Rosenzweig et al., 2002; Climate Risk Management Limited, 2005; Nicholls et al., 2008), which if included are very likely to increase aggregate estimates of climate damages. There is now greater attention on the risk of sea level rise from melting of the Greenland and West Antarctic ice sheets, which may be more rapid than previously thought and occur with smaller increases in temperature, potentially increasing the magnitude of sea level rise and associated damages for a given amount of temperature increase and for a given point in time (Core Writing Team et al., 2007; Mote, 2007; Pfeffer et al., 2008, Rahmstorf et al 2007).

New categories of impacts are also emerging for which market and non-market damages are as yet unclear, but may be significant. One example is ocean acidification, which may create significant adverse impacts on coral reefs, fisheries, and other aspects of marine ecosystems (e.g., Orr et al., 2005). A related, more general, example is the concept of ecosystem services, providing economic valuation of functions provided by natural ecosystems such as forests preserving watersheds by preventing soil erosion, marshes filtering toxins and buffering against storm surges, and species pollinating crops and providing sources for new medicines (e.g., Daily et al., 2000). Increasingly, ecosystem services are becoming broadly recognized as valuable natural assets that may be expensive or impossible to replace if degraded or lost, but the incorporation of ecosystem services into economic accounting is still in its infancy (Daily and Matson, 2008; Mäler et al., 2008).

Climate impacts from changes in water resources are also an increasing source of concern in certain regions, and such impacts are not generally a large component in impact estimates incorporated in IAMs (e.g., water resource impacts in DICE are viewed as negligible). For example, semi-arid climates around the world (including areas such as California and other parts of the North American West) are projected to become dryer (Meehl et al., 2007), and to see large changes in patterns of water demand and supply, as warmer conditions cause more precipitation to fall as rain instead of snow, reducing snowpack buildup and the availability of water from this important source during dry summer months, as well as increasing urban and particularly agricultural water demand (e.g., Hayhoe et al., 2004; Core Writing Team, 2007).

Models and the impact estimates on which they are based generally also treat impacts in different sectors separately, and do not take into account interactions between sectors. In reality, impacts can concurrently affect multiple sectors in the same region, potentially leading to further damages than if each impact occurred in isolation. For example, more frequent or intense heat waves can simultaneously cause increased public health effects (heat-related mortality and hospitalizations, lost productivity due to illness, aggravation of respiratory illness from degraded air quality, etc.) and disruption of electricity generation and/or transmission, which can lead to further heat exposure if air conditioning fails.

IAM developers, of course, update their models over time in an attempt to reflect the latest science. Updates to the DICE-2007 model are described above. The most recent version of FUND updates model estimates of ecosystem impacts (Anthoff and Tol, 2008). The probabilistic structure of PAGE generates a range of relationships between temperature and damages, and this distribution can be adjusted as new information emerges. See, for example, the application of PAGE in the Stern Review (Stern, 2007), where greater inclusion of non-market impacts results in estimates of higher net damages (also see Hope, this volume).

Nevertheless, not all problematic elements can be addressed in this way. As mentioned above, MacCracken (this volume) presents a detailed discussion of the challenges involved in quantifying the environmental and social impacts of climate change in economic terms, topics discussed more abstractly by Ackerman et al. and Yohe (this volume).

The Bottom Line (Recommendations to Decision Makers)

IAMs are powerful tools that, as is the case for any model, must contend with an ever-changing body of underlying literature. Estimates of climate impacts incorporated into IAMs necessarily lag behind the scientific literature on climate impacts. This is one of many sources of uncertainty in IAMs that significantly affect model results, particularly when IAMs are employed in an optimization framework for CBA. This sensitivity is illustrated by the very different optimization results among IAMs described here. Different IAMs make different assumptions about many key scientific uncertainties and aspects of socioeconomic development. There is no one “correct” set of choices, just as there is no one “optimal” solution for a pathway of future emissions.

Thus, it is very important to understand these sources of uncertainty and the limitations of such modeling exercises when considering CBA results and IAM results in general as a source for policy guidance. The most important information to be gleaned from IAM efforts is not the specific numerical results of a particular modeling analysis, but broader insights into the general structure of the policy challenge posed by climate change that come from examining results across models and understanding the relative importance of differences in assumptions that drive the results. The papers in this volume by Hope, Anthoff, and

Newbold provide useful examples of the appropriate use of the PAGE(2002), FUND, and DICE models, respectively, to generate key insights.

In the context of the representation of climate impacts in IAMs, the following conclusions can be drawn:

- Explicit incorporation of (i) a broader set of climate impacts (e.g., non-market impacts), (ii) new advances in scientific understanding of climate impacts (e.g., impacts from extreme weather events and ocean acidification), and (iii) existing uncertainty in the severity of climate impacts (e.g., a probabilistic representation as in PAGE, rather than a deterministic representation as in DICE), will generally increase climate damages in IAMs.
- No IAM currently accounts for all of these factors and all therefore are likely to underestimate the magnitude of damages from climate change. Thus, when employed for CBA, they are likely to underestimate optimal emissions reductions.

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WORKSHOP PROCEEDINGS

Assessing the Benefits of Avoided Climate Change: Cost-Benefit Analysis and Beyond

The Social Cost of CO_2 and the Optimal Timing of Emissions Reductions under Uncertainty

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May 2010

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The Social Cost of CO_2 and the Optimal Timing of Emissions Reductions under Uncertainty

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Abstract

The social cost of CO_2 is the extra climate change impact that would be caused by the emission of one more tonne of CO_2 into the atmosphere. PAGE2002 is an integrated assessment model that can find the social cost of CO_2. It uses simple equations to capture complex climatic and economic phenomena. This is justified because all aspects of climate change are subject to profound uncertainty. Using the same inputs as in the Stern review, PAGE2002 finds the mean social cost of CO_2 in 2008 to be $120 per tonne of CO_2, growing at about 2 percent per year, with a wide range from $25 to $320, almost independent of the emissions scenario on which the extra tonne of emissions is superimposed. Optimal global emissions fall to 45 percent of their year 2000 levels by 2020, and to 25 percent of their year 2000 levels by 2060. The theoretically correct price on CO_2 is the social cost of CO_2 on the optimal emission path. As the social cost of CO_2 does not vary much with the emissions path, we don't need to be too worried about the exact details of the optimal path when setting a price on CO_2. On the other hand, seemingly technical choices, about equity weights, the exponent of the impact function and the pure time preference rate, have almost as much influence as the more obvious climate sensitivity on policy-relevant results like the social cost of CO_2.

Introduction

There is now a great deal of interest in attacking the problem of climate change by putting a price on emissions of carbon dioxide (CO_2) (see for instance, Gore, 2007, Nordhaus, 2009). The social cost of CO_2 is the extra climate change impact that would be caused by the emission of one more tonne of CO_2 into the atmosphere. The polluter pays principle means that anyone who emits a tonne of CO_2 should be charged the social cost of CO_2 for doing so, either through a tax, or through the purchase of a tradable permit. Finding the social cost of CO_2 requires an integrated assessment model – a model which combines scientific and economic information to produce policy-relevant results.

The PAGE2002 model

PAGE2002 is such an integrated assessment model, estimating the temperature rises and impacts that result from a user-specified emissions scenario. It is the integrated assessment model used by the Stern review in its calculation of impacts and social costs (Stern, 2007). It uses a number of simplified formulas to represent the complex scientific and economic interactions of climate change. A full description of the model can be found in Hope (2006) and Hope (2008). Most of the model's coefficients and data ranges are calibrated to match the projections of the Third Assessment Report of the Intergovernmental Panel on Climate Change (Houghton et al., 2001).

The model includes ten time intervals spanning the 200 years from 2000 to 2200, divides the world into eight regions, and explicitly considers three different greenhouse gases (carbon dioxide, methane, and sulphur hexafluoride) with other gases included as an excess forcing projection.

Three types of impact are calculated:

- economic impacts, which are impacts on marketed output and income, in sectors such as agriculture and energy use, that are directly included in GDP;
- non-economic impacts, which are impacts on things like health and wilderness areas which are not directly included in GDP; and
- discontinuity impacts, which are the increased risks of climate catastrophes, such as the melting of the Greenland or West Antarctic Ice Sheet.

These three types of impacts are measured in economic terms and summed to calculate total impacts. Of course the quality and uncertainty in the estimates are heavily dependent on the ability of economists to make the primary measurements which the PAGE2002 model simulates. This ability is reasonable for the economic impacts, limited for the non-economic impacts, and rudimentary for the discontinuity impacts, which motivates the use of probability distributions throughout the model.

The PAGE2002 model uses relatively simple equations to capture complex climatic and economic phenomena. This is justified because the results approximate those of the most complex climate simulations, as shown by Hope (2006), and because all aspects of climate change are subject to profound uncertainty.

To express the model results in terms of a single 'best guess' could be dangerously misleading. Instead, a range of possible outcomes should inform policy. PAGE2002 builds up probability distributions of results by representing 31 key inputs to the impact calculations by probability distributions, making the characterization of uncertainty the central focus, as recommended by Morgan and Dowlatabadi (1996); the most frequently reported results from PAGE are the mean outcomes from 10,000 runs of the model, and the 5 – 95 percent confidence intervals representing the uncertainty in the outputs.

The social cost of CO_2

The top row of table 1 shows the social cost of CO_2 calculated by PAGE2002 with projections of GDP, population and emissions of greenhouse gases taken from IPCC Scenario A2 (Nakicenovic and Swart, 2000) to 2100, and constant thereafter. The pure time preference rate is 0.1 percent per year, and the equity weight is 1, as in the Stern review, meaning that a $1 loss to someone with an income of $1000 per year is counted as ten times as bad as a $1 loss to someone with an income of $10,000 per year. This gives consumption discount rates derived from the Ramsey rule of the order of 1.5 percent per year in annex 1 countries (i.e. industrialized nations like the USA, Germany, and Japan), higher in non-annex 1 countries (i.e. developing countries), and declining over time. This consumption discount rate does not take account of the covariance between climate impacts and consumption that could perhaps make the discount rate lower still.

Table 1. The social cost of CO_2 in 2008, by scenario*

2000 - 2200	**$US(2008)**		
	5 percent	**mean**	**95 percent**
Scenario A2	25	120	320
'450' scenario	20	125	370

**Based on 10000 PAGE2002 model runs using 0.1 percent pure time preference rate*

Under the A2 scenario, PAGE2002 projects the mean CO_2 concentration to be about 815 ppm by 2100 and the mean global mean temperature to be 4.1 °C above pre-industrial levels by 2100. The mean social cost of CO_2 in 2008 is $120 per tonne of CO_2, but the range is wide, from $25 to $320. This wide range is a simple consequence of the uncertainties that surround most parts of the climate change issue, both scientific and economic.

The second row of table 1 demonstrates a result that surprises many people: the social cost of CO_2 hardly depends at all on the emissions scenario on which the extra tonne of emissions is superimposed. In the second row, the social cost of CO_2 is calculated for a scenario with the same projections of GDP and population, but with emissions of greenhouse gases aimed at stabilizing the concentration of CO_2 at 450 parts per million (ppm) (Wigley, 2003). The mean social cost of CO_2 in 2008 under this '450' scenario is $125 per tonne of CO_2; this mean value and the range are almost the same as under the business as usual A2 scenario.

The '450' scenario involves aggressive abatement measures, with global emissions of CO_2 35 percent lower in 2050 and 70 percent lower in 2100. As PAGE2002 includes stimulation of natural CO_2 as a bad feedback loop (using the IPCC estimates of less effective uptake of CO_2 by oceans as temperature increases), it actually predicts a mean CO_2 concentration for the '450' scenario that is slightly higher than 450 ppm in 2100, but still substantially lower than the A2 scenario. Mean CO_2 concentration is about 515 ppm by 2100, and mean global mean temperature is 3.1 °C above pre-industrial by 2100.

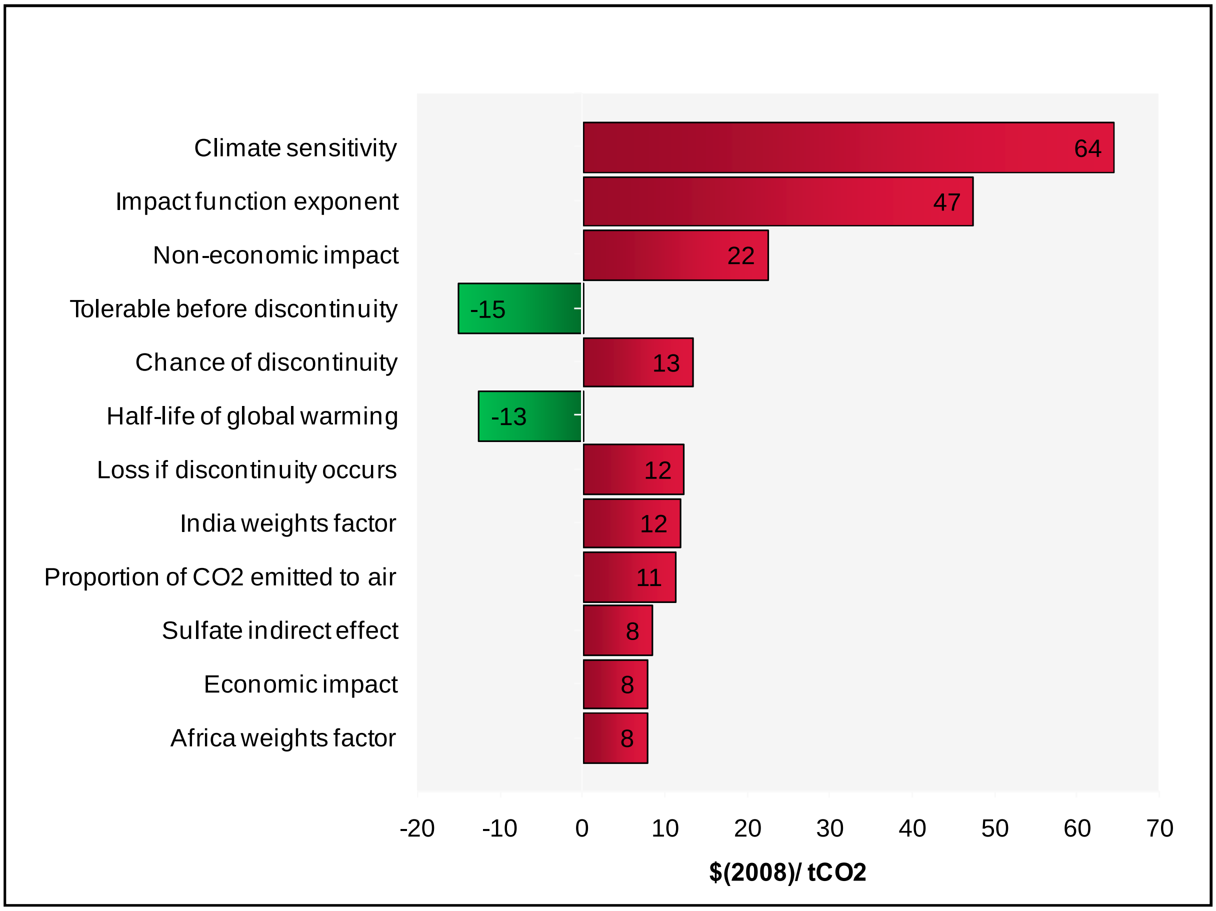
The reason why the social cost of CO_2 does not vary between the scenarios is not straightforward. It is caused by the interplay between the logarithmic relationship between forcing and concentration, which makes one extra ton under the lower concentrations of the '450' scenario cause about twice the temperature rise that it causes under the A2 scenario, and the nonlinear relationship of impacts to temperature which makes one extra degree of temperature rise on top of the lower temperatures of the '450' scenario cause only about half the extra impact it causes under the A2 scenario. These two effects roughly cancel each other out, leaving the mean social cost of CO_2 the same under each scenario. This empirical result is not unique to this particular combination of baseline and abatement target and appears to be robust (Hope, 2006a). The theoretically correct price on CO_2 is the social cost of CO_2 on the optimal emission path. As the social cost of CO_2 does not vary much with the emissions path, we don't need to be too worried about the exact details of the optimal path when setting a price on CO_2.

Major influences on the social cost of CO_2

The social cost of CO_2 may not vary much with the path of emissions, but it is strongly affected by several of the variables in the PAGE2002 model. Figure 1 shows the top 12 influences on the social cost of CO_2 under the A2 scenario. For each input, the bar shows the amount by which the social cost of CO_2 would increase if the input in question increased by one standard deviation.

The three top influences are the climate sensitivity, which is the temperature rise that would occur for a doubling of CO_2 concentration, the impact function exponent, which measures how curved the impact function is with temperature, and the non-economic impact parameter, which measures the non-economic impact for a 2.5 °C temperature rise. All three are positively correlated with the social cost of CO_2. For the climate sensitivity, an

Figure 1. Major influences on the social cost of CO_2 *(Source: PAGE2002 model runs for scenario A2 using 0.1 percent pure time preference rate)*



increase of one standard deviation, which is about 0.75 °C as the climate sensitivity takes a triangular distribution with minimum, most likely and maximum values of 1.5, 2.5 and 5 °C (Houghton et al., 2001), would increase the social cost of CO_2 by $64 per ton. Having this quantified measure of influence enables us to estimate what would happen to the social cost of CO_2 if one of the higher estimates of climate sensitivity that have been produced since the IPCC third assessment report turn out to be correct. The non-economic impact parameter is about three times as influential as the economic impact parameter, largely because the model assumes that a great deal of the economic impacts can be adapted to, at least in rich countries.

Three of the next four influences relate to the discontinuity impact. The temperature rise that can be tolerated before there is any chance of a discontinuity is negatively correlated with the social cost of CO_2, as a rise in this parameter leads to a lower social cost of CO_2. It is a bit surprising that the discontinuity impact should have such a large influence on today's social cost of CO_2, as any discontinuity that might occur is far more likely to happen in the 22nd century than in this one. But the discontinuity is large enough, and the discount rate small enough, that it does indeed emerge as a major influence. The only reason that the discount rate itself does not appear as a major influence is because in these results the pure time preference rate is fixed at the single value of 0.1 percent per year, and the equity weight at the single value of 1, used in the Stern review.

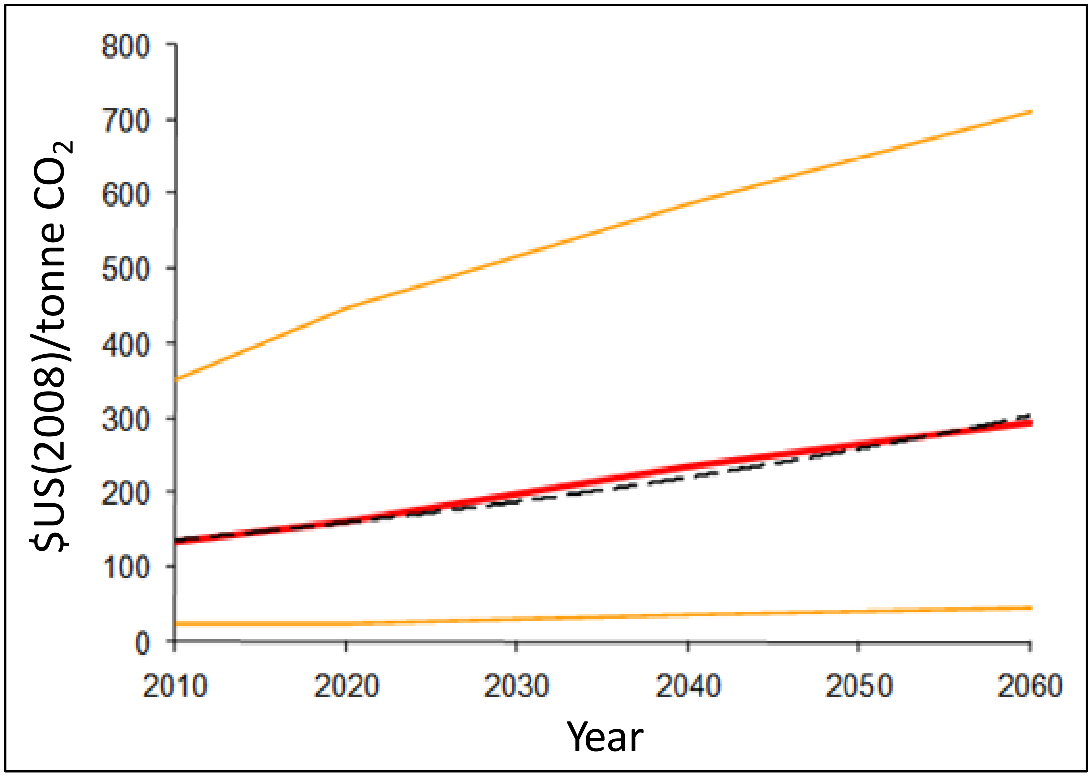
That the major influences divide into six scientific and six economic parameters is another strong argument for the building of integrated assessment models such as PAGE2002. Models that are exclusively scientific, or exclusively economic, would omit parts of the climate change problem which still contain profound uncertainties.

Growth in the social cost of CO_2 over time

Figure 2 shows how the PAGE2002 estimates for the social cost of CO_2 vary with the date that the carbon dioxide is emitted under the A2 scenario. The thicker, red, line shows the mean values, the thinner, orange lines show the 5 percent and 95 percent uncertainty points on the probability distribution. On average, the mean values increase by just under 2 percent per year, as shown by the dashed black line in the figure; by 2040 the mean estimate has risen to about $200 per tonne of CO_2.

The social cost of CO_2 grows as we move closer to the time that the most severe impacts of climate change are likely to occur. The rate of growth is kept down somewhat by the time horizon of 2200 for calculating impacts; with a 0.1 percent pure time preference rate, omitting any impacts after 2200 gives an increasingly large downward bias to estimates of the social cost of CO_2 as we move into the future.

Figure 2. The social cost of CO_2 by calendar year as estimated from PAGE2002 model runs for scenario A2 using 0.1 percent pure rate of time preference.



Optimal emission reductions

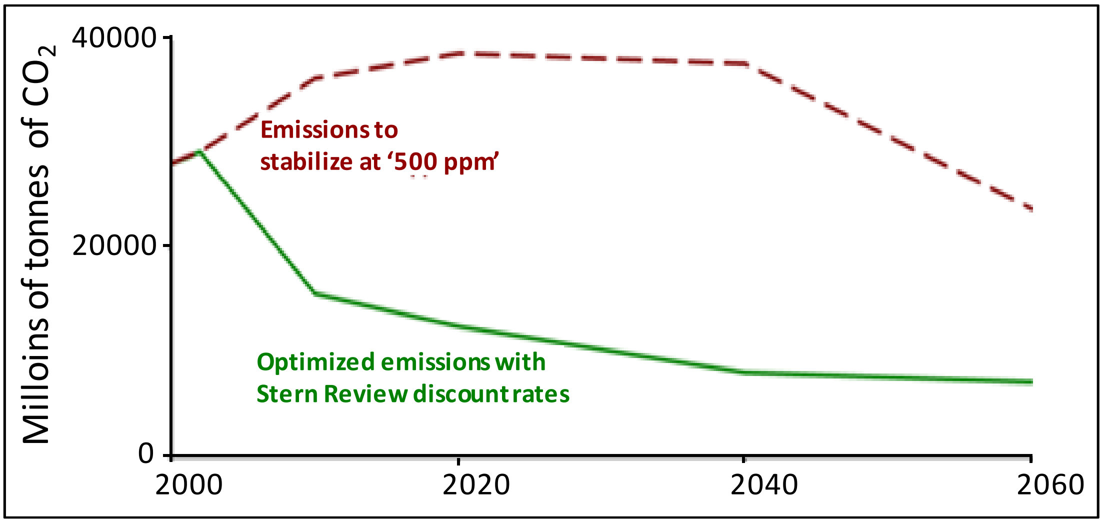
Optimal emissions can be defined as the path of emissions which minimise the mean net present value of the sum of climate change impacts and abatement costs. Figure 3 shows the optimal emissions up to 2060 calculated by the PAGE2002 model, using the Stern review assumptions which give the social cost of CO_2 results reported above.

The Common Poles Image (CPI) scenario is used as the business as usual scenario (den Elzen et al, 2003), rather than the A2 scenario as the initial analysis was performed for the Innovation Modelling Comparison Project which standardised on this BAU scenario, and the GDP, population and non-CO_2 greenhouse gas emissions from this scenario are used throughout the analysis of optimal emissions.

The optimal global emissions fall to 45 percent of their year 2000 levels (a 55 percent emissions reduction) by 2020, and to 25 percent of their year 2000 levels (a 75 percent reduction) by 2060. These emissions give mean CO_2 concentrations in 2100 of 445 ppm, with a 5 to 95 percent range of 415 to 485 ppm, and annual mean global mean temperature in 2100 of 2.6 °C above pre-industrial levels, with a 5 to 95 percent range of 1.5 to 4.1 °C.

For comparison, figure 3 also shows the 500 ppm CO_2 emission path, developed using the MAGICC model (Wigley, 2003). Due to a feedback loop in PAGE2002's carbon cycle that simulates the ocean's decreasing carbon sequestration ability as the temperature rises, PAGE2002's mean expected concentrations in 2100 are higher than the stated value for the scenario by around 70 ppm, with a fairly broad range. Therefore this path is described as '500 ppm', rather than 500 ppm, in figure 3. What is clear is that if the Stern review conclusions are accepted, the optimal emission cutbacks justified by them are much steeper than those which would lead to the stabilization of CO_2 concentrations at 500 ppm or more of CO_2.

Figure 3. Optimal emissions of CO_2 by calendar year as estimated by PAGE2002 model runs from CPI baseline using 0.1 percent rate of pure time preference.



Alternative assumptions and their effect on the social cost of CO_2

To show the effect of making changes to the inputs to the PAGE2002 model, we can try out an alternative set of assumptions and see the changes in the social cost of CO_2 and the major influences on the result. The alternative assumptions reflect some of the advances in understanding and concerns that have been raised since the Stern review's publication. The social cost of CO_2 that results should be understood as an illustration of the PAGE2002 model's ability to use some plausible alternative inputs, but not a fully updated and peer-reviewed calculation.

Pure time preference rate and equity weight

The Stern review's choice of a low 0.1 percent per year pure time preference rate has been a point of contention within the economics community. Many critics of the review favoured higher discount rates (e.g., Nordhaus, 2007; Tol and Yohe, 2006), while the review's authors continued to defend a pure time preference rate close to zero (Dietz et al., 2007). Others[1] point out that 'we do not observe "the" market rate of interest, but rather a multitude of different rates of return to assets having different characteristics' and so observations of market interest rates are of limited use for evaluating long-term public investments like those required to tackle climate change. Rather than trying to resolve this dispute, the alternative assumptions assume a range of possible pure time preference rates of <0.1, 0.5, 1> percent per year (here, and throughout the rest of this paper, the triangular brackets denote a triangular probability distribution with <minimum, most likely, maximum> parameter values). Similarly, the alternative assumptions have a range of equity weights of <0.5, 1, 2>. Combining the maximum values would give a consumption discount rate of about 3 - 4 percent per year, if growth rates in per capita GDP are in the range of 1 – 2 percent per year.

Adaptation

The PAGE2002 defaults, adopted by the Stern Review, assume that substantial, nearly costless adaptation will occur; the reported damage estimates are for damages remaining after that adaptation takes place. Specifically, PAGE assumes that in developing countries, 50 percent of economic damages are eliminated by low-cost adaptation. In OECD countries, the assumption is even stronger: 100 percent of the economic damages resulting from the first 2 degrees of warming, and 90 percent of economic damages above 2 degrees, are eliminated. For non-economic, non-catastrophic damages, adaptation is assumed to remove 25 percent of the impact everywhere. No adaptation is assumed for discontinuity damages.

These adaptation assumptions seem optimistic to some commentators, particularly for the economic sector (Ackerman et al., 2009). So the alternative assumptions have adaptation

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[1] See the paper by Ackerman et al. in this volume.

that is only about half as effective: in developing countries, 25 percent of economic damages are eliminated by low-cost adaptation, while in OECD countries, 100 percent of the economic damages resulting from the first 1 degree of warming, and 50 percent of economic damages above 1 degree, are eliminated.

Discontinuity

PAGE2002 assumes that a threshold temperature must be reached before catastrophic events, which would lead to impacts on GDP an order of magnitude higher than 'normal' climate impacts, become possible; once that threshold is crossed, the probability of catastrophe gradually rises along with the temperature. Two of the uncertain parameters are involved here. One is the threshold temperature, with default values of <2, 5, 8> degrees C above pre-industrial in the Stern analysis. A second parameter is the rate at which the probability of catastrophe grows, as the temperature rises past the threshold. The default has the probability of catastrophe increasing by <1, 10, 20> percentage points per degree C above the threshold.

Much of the recent discussion of potential catastrophes, such as the loss of the Greenland or West Antarctic ice sheets, has suggested that they become possible or even likely at temperatures below the default "most likely" threshold of 5 °C of warming (e.g., Rahmstorf, 2007). So the alternative assumptions change the threshold temperature to <2, 3, 4> degrees Celsius, and the growth in the probability of catastrophe to <10, 20, 30> percentage points per degree Celsius above the threshold.

The shape of the damage function

PAGE2002, like most integrated assessment models, assumes economic and non-economic climate damages are a function of temperature, using a simple equation of the form:

$$\text{Damages} = aT^N$$

Here, 'a' is a constant, 'T' is the temperature increase, and 'N' is the exponent governing how fast damages rise. If N = 2, then 4 °C is four times as bad as 2 °C; if N = 3, then 4 °C is eight times as bad, etc.

PAGE2002 treats the exponent N as one of the uncertain parameters that is allowed to vary in the uncertainty analysis, with a default input of <1, 1.3, 3>. Based on recent scientific assessments of climate impacts (Smith et al., 2009), the "most likely" value of 1.3 now appears too low. In the alternative assumptions we set the exponent at <1.5, 2.25, 3>. This alternative keeps the exponent within the same range used in the Stern Review, but weights the higher end of the range more heavily; it assumes that the exponent is most likely to be a little more than 2, the value used in many recent models (e.g., Nordhaus, 2008).

Non-economic impacts and regional weights

The PAGE2002 defaults have non-economic impacts as <0,0.7,1.5> percent of GDP in the focus region (the European Union) for a 2.5 degC rise in temperature above pre-industrial levels, lower in other OECD regions, and higher in most developing countries, except China, with regional multipliers as shown in Table 2.

Some studies have shown that many economic models omit a range of impacts that actually may prove to be important (Watkiss et al., 2006; Ackerman et al., 2009). Commentators have also noted that regional weights giving more importance to impacts in other regions of the world do not necessarily fit with actions taken in other policy areas that affect developing countries (Gardiner, 2004).

Table 2. Default regional weight factors in PAGE2002 as a multiple of EU values
Source: Hope (2006)

Region	Minimum	Mode	Maximum
Eastern Europe & FSU weights factor	-1	-0.25	0.2
USA weights factor	0	0.25	0.5
China weights factor	0	0.1	0.5
India weights factor	1.5	2	4
Africa weights factor	1	1.5	3
Latin America weights factor	1	1.5	3
Other OECD weights factor	0	0.25	0.5

To illustrate these general ideas, the alternative assumptions increase the non-economic impacts to <0.2,1,2> percent of GDP in the focus region and increase the USA regional multiplier to <0.5, 1, 1.5>. However, they decrease all other regional multipliers to one half of their value in table 2.

Results—sensitivity of social cost of CO_2 to alternative assumptions

How do these alternative assumptions affect the social cost of CO_2? Table 3 shows that the mean estimate decreases from $120 per tonne of CO_2, with the default inputs, to $95 per tonne of CO_2 with the alternative assumptions, a drop of about 20 percent. The 5 percent and 95 percent points drop by a similar percentage, so the shape of the probability distribution of the social cost of CO_2 has not changed a great deal. The primary reason for the decrease is the larger average discount rate in the alternative assumptions, with smaller contributions from decreased non-economic impact multipliers in developing countries. These changes outweigh the combined effect of other alternative assumptions that would tend to increase the social cost of CO_2, including less effective adaptation, greater probability and sensitivity to discontinuity, and a steeper damage function. This result illustrates the strong sensitivity of the estimated social cost of CO_2 to the chosen discount rate.

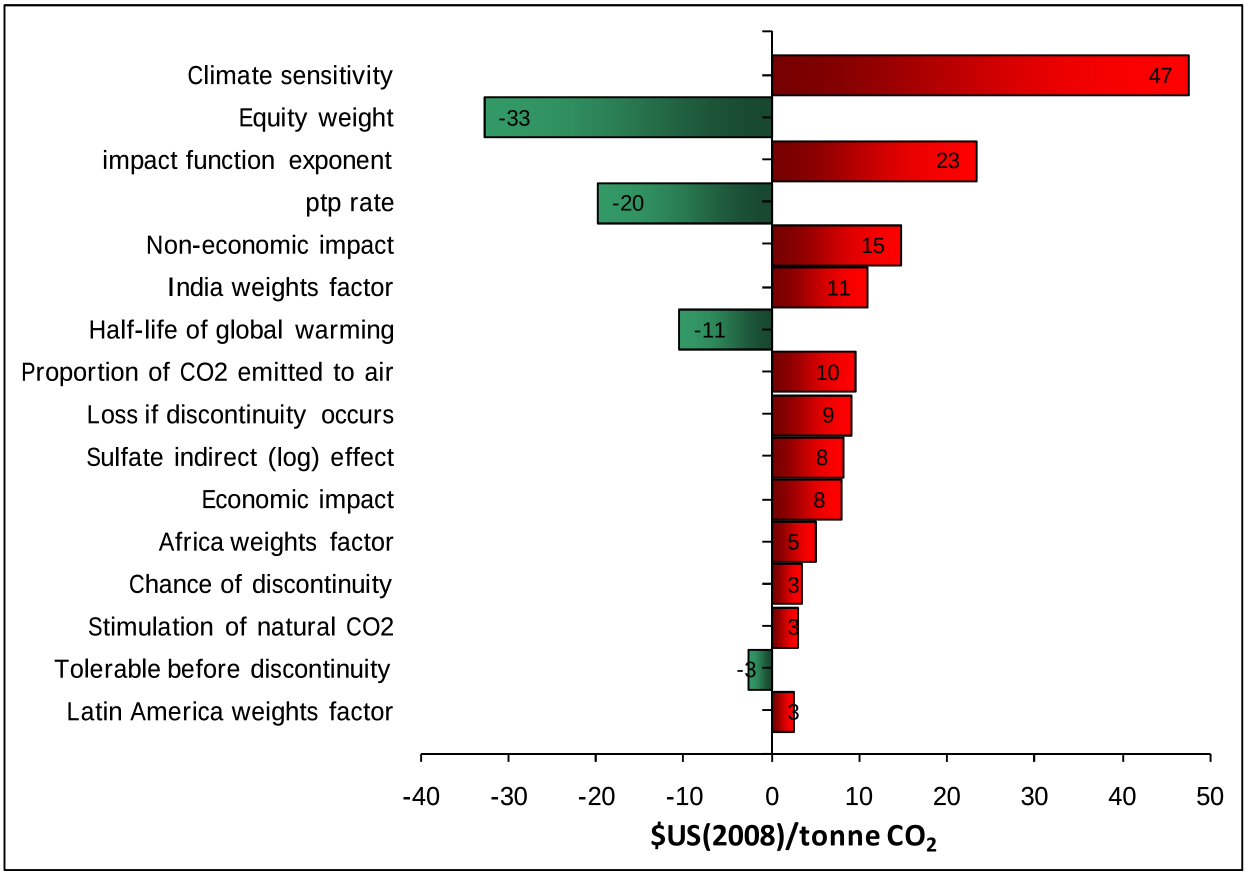
Table 3. The social cost of CO_2 in 2008, by input assumption *(Source: 10000 PAGE2002 model runs for scenario A2)*

2000 - 2200		**$US(2008)**	
	5 percent	**mean**	**95 percent**
Default assumptions	25	120	320
Alternative assumptions	20	95	250

Figure 4 shows the top influences on the social cost of CO_2 with the alternative assumptions. For each input, the bar shows the amount by which the social cost of CO_2 would increase if the input in question increased by one standard deviation.

- The climate sensitivity is still the top influence; an increase of one standard deviation would now increase the social cost of CO_2 by $47 per ton.
- Now the equity weight becomes the second most important influence and an increase of one standard deviation would decrease the social cost of CO_2 by about $35 per ton. Recall that in the original results, the discount rate was fixed at the single value of 0.1 percent per year, and the equity weight at the single value of 1, used in the Stern review, so they did not appear as influences in figure 1. Figure 4 shows that a higher equity weight leads to a lower social cost of CO_2. This might seem counter-intuitive, but it comes about because of the logical link between equity weights and discount rates; as the equity weight goes from 0.5 to 2, the consumption discount rate rises according to Ramsey's rule (consumption discount rate = pure time preference rate + equity weight x growth in GDP per capita), and the drop in present values that results far outweighs the increase in the valuation of impacts in poor countries that a higher equity weight brings.
- The impact function exponent is now the third most influential input, down from $47 to $23 for a one standard deviation rise. This drop is at least partly because the range of the exponent is now smaller (i.e. one standard deviation is now a smaller change in the parameter).
- The pure time preference rate is the fourth most important parameter. A higher pure time preference rate leads to a lower social cost of CO_2 as impacts in the future are discounted more.
- The non-economic impact parameter is now only about twice as influential as the economic impact parameter, because we have now assumed that adaptation will be less effective at reducing the economic impacts.
- The inputs relating to the discontinuity impact are now less important than with the default inputs, despite the probability of a discontinuity being higher with the alternative assumptions. For instance, the influence of the chance of a discontinuity has decreased from $13 to $3. This is because the higher mean discount rates under the alternative assumptions make impacts that occur in the far future less important.

Figure 4. Major influences on the social cost of CO_2 with alternative assumptions in PAGE 2002.



Conclusions & Recommendations

The results with these alternative assumptions demonstrate the flexibility of the PAGE2002 model, and the importance of using a model to lay bare the interactions between the different parts of the climate change problem, and provide the best evidence we have to inform climate change policy.

The best evidence must include an assessment of the risks and uncertainties as well as most likely or mean results. With our present knowledge, the social cost of CO_2 has a range of at least an order of magnitude; this has implications, suggesting that flexibility and detection of surprises will be important components of a good policy towards climate change.

The details matter. Seemingly technical choices, about equity weights, the exponent of the impact function and the pure time preference rate, have almost as much influence as the more obvious climate sensitivity on policy-relevant results like the social cost of CO_2.

Acknowledgement

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Background Papers for Session 4:

Advances in the Economic Analysis of the Benefits of Climate Policy

WORKSHOP PROCEEDINGS

Assessing the Benefits of Avoided Climate Change: Cost-Benefit Analysis and Beyond

Federal Decision-Making on the Uncertain Impacts of Climate Change: Incremental vs. Non-Incremental Climate Decisions

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May 2010

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Federal Decision-Making on the Uncertain Impacts of Climate Change: Incremental vs. Non-Incremental Climate Decisions

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Abstract

From judicial, to executive, to legislative decisions, all three branches of the U.S. federal government have developed a more urgent need for information on the potential impacts of climate change. The information requirements vary dramatically across the broad range of legal, energy, climate, and other decisions. This paper begins with a review of recent federal decision processes that have drawn on climate change impacts information. The paper then defines the impacts information requirements of these decisions by characterizing the types of decisions and the physical and economic nature of greenhouse gases and climate change. Throughout the paper, a clear distinction is drawn between policies with incremental effects on climate and those designed to manage climate. The paper goes on to describe the state of impacts knowledge in light of the information requirements of incremental and non-incremental decisions and discusses decision-making challenges associated with using the available information. The paper concludes by deriving fundamental principles and components of an analytical framework for developing and utilizing climate change impacts information in federal decision-making, and identifies critical information gaps that should be addressed.

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[1] Steven Rose was asked to write this paper while still at the U.S. Environmental Protection Agency (EPA). However, this paper does not reflect the views of EPA or EPRI and its members.

1. Introduction

Over the past three years, the United States government has developed a more urgent interest and need for information on observed and potential impacts of climate change. All three branches of the federal government—judicial, executive, and legislative—have confronted decisions that engendered an additional appetite for impacts information. The types of decisions covered a varied and broad range of issues, including domestic legal, energy, climate, and species protection, as well as the international negotiations process. While each decision called for information on impacts, the type and threshold of information required differed. This paper decomposes and defines the climate change impacts information needs of federal decision-making, and discusses the challenges associated with the information currently available for decisions that can have either minor or significant climate implications. The paper draws a clear distinction between policies with incremental climate effects and those with larger impacts that are designed to manage climate change. The paper assesses the research literature in light of these two types of decisions. The paper then derives a fundamental analytical framework for developing and utilizing climate change impacts information in federal decision-making.

Recognizing and defining information requirements is valuable for designing analyses, assembling the necessary data, and identifying information gaps. The impacts information required can be thought of as being determined by two factors: the type of decision being made and the scientific and economic nature of the problem. This paper characterizes these factors. Understanding the state of the art is also essential for making actual climate related decisions. Recognizing the state of current information, as well as what additional information will likely be available in the future, is fundamental to characterizing the information challenges to climate change decision-making and the types of decisions that are supported. It is also valuable for defining research priorities.

Section 2 of this paper provides with an overview of recent federal decision processes that have utilized some form of climate change impacts information. Section 3 characterizes the types of decisions at issue as well as the scientific and economic nature of greenhouse gas (GHG) emissions and climate change, which has implications for the scope and approach of analysis, including cost-benefit analysis, net benefit assessments, and discounting. The result is a topography of impacts analyses and information requirements. Section 4 considers the state of relevant climate change knowledge and decision-making challenges in the context of important decision-making issues. Section 5 derives the principles and components of an analytical framework for assessing impacts, and it identifies several information development priorities. The paper should be considered an analytical complement to the recent National Research Council publication that recommends organizational processes for developing, disseminating, and facilitating the use of climate change vulnerability and response information (NRC, 2009).

2. Recent federal decision processes

Over the past three years, all three branches of the federal government have confronted decisions that required climate impacts information. The decisions covered a varied and broad range of issues, including domestic legal, energy, climate, and species protection, as well as the international negotiations process. This section briefly describes these various decision types.

Legal decisions. Over the past three years, federal courts were confronted with two notable cases where climate change impacts were critical issues.

- *U.S. Supreme Court (2007)*. The U.S. Supreme Court ruled on whether the U.S. Environmental Protection Agency (EPA) had the authority under the Clean Air Act and obligation to make a determination on whether GHG emissions from the U.S. transportation sector "cause or contribute to air pollution that may reasonably be anticipated to endanger public health or welfare."[2] The court ruled that EPA did have both the authority and the responsibility. In 2009, EPA issued a proposed endangerment finding for public comment and subsequently finalized the finding at the end of year (see the Clean Air Act discussion below).
- *U.S. 9th Circuit Court (2007).* The U.S. 9th Circuit Court ruled on whether the U.S. National Highway Transportation and Safety Administration (NHTSA) was arbitrary and capricious in implying a zero value for the benefits of reduced GHG emissions in setting new Corporate Average Fuel Economy (CAFE) standards for light trucks for model years 2008-2011. The court ruled that NHTSA could not assume a zero dollar value and needed to develop an estimate.[3]

Energy policy. A variety of energy policies were caught in the wake of the 9th Circuit Court's decision referenced above, and agencies were confronted with the challenge of having to consider the monetary value of changes in GHG emissions associated with their proposed rules.

- *CAFE standards (2008-2009)*. Following the 9th Circuit's decision, NHTSA issued a proposed rulemaking for CAFE standards for passenger vehicles and light trucks for model years 2011-2015 based on, among things, NHTSA's own estimates for the domestic marginal benefit of reducing GHG emissions.[4] NHTSA received comments on the estimates, as well as the proposed rule in general, and issued a Final Environmental Impact Statement associated with the rule. However, the final rule

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[2] Massachusetts v. EPA, 127 S. Ct. 1438 (2007).

[3] Center for Biological Diversity vs. National Highway Traffic Safety Administration, United States Court of Appeals for the Ninth Circuit, No. 06-71891, November 15, 2007.

[4] NHTSA's proposed standard was based on a value of \$7/tCO$_2$ in 2011 (2006\$), about \$6/tCO$_2$ in 2007 given NHTSA's assumed growth rate of 2.4 percent/yr. NHTSA also performed sensitivity analyses with a range of \$0 to \$14/tCO$_2$ (approximately \$0 to \$13/tCO$_2$ in 2007). *DOT (NHTSA) Average Fuel Economy Standards, Passenger Cars and Light Trucks, MY 2011-2015,* http://www.nhtsa.dot.gov/portal/site/nhtsa/menuitem.43ac99aefa80569eea57529cdba046a0/.

was not issued before the end of 2008 and was passed to the Obama administration, which placed a hold on all pending regulations. NHTSA has since issued a final rule for only model year 2011 vehicles that includes revised marginal benefit estimates and a declaration to work with other agencies to develop future estimates. NHTSA found the revised estimates to be inconsequential in setting the standard.[5]

- *Improved appliance efficiency (2008-2009)*. The U.S. Department of Energy (DOE) recently finalized energy conservation standards for residential gas kitchen ranges and ovens that were initially proposed under the Bush administration. In separate rulemakings, DOE issued new energy conservation standards for commercial air conditioning equipment in 2008, beverage machines in 2009, and small electric motors in 2010. All four sets of standards are based on specific monetary estimates of the marginal benefit of reduced GHG emissions, though not the same estimates.[6] The small motors final rule is the first to use newly derived marginal benefits estimates from a 2010 interagency analytical guidance document.[7]
- *Twenty-in-Ten (2007)*. President Bush issued an executive order to reduce U.S. transportation gasoline use by twenty percent by 2010 through a combination of alternative fuels and improved vehicle efficiency.[8] However, the order was

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[5] Average Fuel Economy Standards, Passenger Cars and Light Trucks, Model Year 2011 (http://www.nhtsa.dot.gov/portal/site/nhtsa/menuitem.43ac99aefa80569eea57529cdba046a0/). The revised marginal benefit estimates were \$2, \$33, and \$80/tCO$_2$ for a change in emissions in 2007 (and in 2007 dollars) and rising at 2.4 percent/year. When the \$33 and \$80 values, which are characterized as global values, were considered, other estimated benefits associated with the policy (i.e., the value of reduced domestic dependence on energy imports) were reduced to zero based on an argument that they were inconsistent with using global values for GHG valuation.

[6] For the gas range and oven and air conditioning equipment standards, DOE used values of \$0 and \$20/tCO$_2$ in 2007 (2007\$) with an assumed growth rate of 2.4%/yr. The proposed gas range and oven rulemaking characterized these estimates as domestic marginal benefit estimates. For the beverage machine standards, DOE used a value of \$20/tCO$_2$ in 2007 (2007\$) with an assumed growth of 3.0%/yr. DOE also carried out sensitivity runs using values of \$5, \$10, \$34, and \$56/tCO$_2$. Gas ranges and ovens standard: Department of Energy, 10 CFR Parts 430, Energy Conservation Program: Energy Conservation Standards for Certain Consumer Products (Dishwashers, Dehumidifiers, Electric and Gas Kitchen Ranges and Ovens, and Microwave Ovens) and for Certain Commercial and Industrial Equipment (Commercial Clothes Washers), Final Rule, *Federal Register*, Vol. 74, No. 66, April 8, 2008, pp. 16040-16096. Air conditioning equipment standard: Department of Energy, 10 CFR Part 431, Energy Conservation Program for Commercial and Industrial Equipment: Packaged Terminal Air Conditioner and Packaged Terminal Heat Pump Energy Conservation Standards: Final Rule, *Federal Register*, October 7, 2008, pp. 58813-58814. Beverage machine standard: Department of Energy, 10 CFR Part 431 Energy Conservation Program: Energy Conservation Standards for Refrigerated Bottled or Canned Beverage Vending Machines; Final Rule. Federal Register, Vol. 74, No. 167, August 31, 2009, pp. 44914-44968. Small electric motors standard: Department of Energy, 10 CFR Part 431, Energy Conservation Program: Energy Conservation Standards for Small Electric Motors; Final Rule, *Federal Register*, March 9, 2010, pp. 10874-10948.

[7] U.S. Government Interagency Working Group on Social Cost of Carbon (2010). Issued with DOE small motors rule March 9, 2010. Four global marginal benefits estimates are provided for emissions changes in 2010 that rise over time: \$4.7, \$21.4, \$35.1, and \$64.9/tCO2 (in 2007\$), where the \$21.4 is regarded as the “central” value and was used in the small motors rule standard.

[8] Executive Order 13432: http://georgewbush-whitehouse.archives.gov/news/releases/2007/05/20070514-2.html.

overtaken by the Energy Independence and Security Act of 2007 (EISA), which included a renewable fuels provision (discussed next).[9]

- *Renewable Fuels Standard (RFS) (2009)*. EISA included, among other things, a mandate for 36 billion gallons of renewable fuels by 2022. The proposed rule was issued May 2009 under the new administration.[10] The rule has a requirement to consider GHG emissions changes, setting minimum lifecycle emissions reduction levels for each renewable fuel type. The proposed rule also uses estimates for the marginal benefit of GHG emissions reductions published by EPA in 2008.[11] The methods and estimates differ significantly from those in NHTSA and DOE rulemakings at that time. Section IV of this paper discusses these EPA estimates. The final rule was issued early in 2010 and included the marginal benefits estimates used in DOE's 2009 beverage machines rule.[12]

Climate policy. Climate change impacts information has only indirectly entered into the discussions of alternative legislative and regulatory proposals for regulating GHG emissions. However, quantified information has seeped into the federal climate policy dialogue surrounding the potential regulation of GHGs under the Clean Air Act.

- *Legislative proposals for GHG mitigation (2008-2009)*. A variety of Congressional proposals for mandated reductions in GHG emissions have been offered, including economy-wide cap-and-trade bills, sector specific emissions control bills, and multi-pollutant bills. For example, leading cap-and-trade proposals were offered in the Senate by Senators Lieberman, Warner, and Boxer and, more recently, by Senators Kerry and Boxer and, in the House of Representatives, by Representatives Waxman and Markey.[13] The proposals focus on GHG emissions reductions, not specifically on climate change impacts.
- *Clean Air Act (2008-2009)*. EPA published an Advanced Notice of Proposed Rulemaking (ANPR) in 2008 discussing the mechanisms and issues associated with potential regulation of GHG emissions under the Clean Air Act.[14] The ANPR also discussed issues associated with estimating the benefits of GHG emissions

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[9] Public Law 110-140.

[10] Environmental Protection Agency, *Federal Register*, 40 CFR Part 80, Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program; Proposed Rule. Vol. 74, No. 99, May 26, 2009, pp. 24904-25143.

[11] U.S. EPA (2008). Also, Section 5.3 of the renewable fuels Draft Regulatory Impact Analysis presents and discusses the EPA marginal benefit estimates and calculates total benefits for emissions reductions associated with the proposed rule (http://www.epa.gov/otaq/renewablefuels/index.htm).

[12] Environmental Protection Agency, 40 CFR Part 80, Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program, Final Rule. Submitted for publication in the Federal Register February 3, 2010. Docket ID No. EPA-HQ-OAR-2005-0161.

[13] S. 3036: Lieberman-Warner Climate Security Act of 2008, as amended by Boxer. S. 1733: Kerry-Boxer Clean Energy Jobs and American Power Act of 2009. H.R. 2454: Waxman-Markey American Clean Energy and Security Act of 2009.

[14] U.S. Environmental Protection Agency, Advanced Notice of Proposed Rulemaking (ANPR): Regulating Greenhouse Gas Emissions under the Clean Air Act, http://www.epa.gov/climatechange/anpr.html.

reductions and applying the estimates.[15] As mentioned above, EPA has since issued a proposed and final endangerment finding for GHG emissions under the CAA. Specifically, the EPA administrator found that concentrations of GHGs in the atmosphere threaten the public health and welfare of current and future generations. The administrator also found that GHG emissions from new motor vehicles and engines contribute to the GHG pollution which threatens public health and welfare. The finding included supporting technical material on GHG emissions, climate change, and impacts.[16] The endangerment finding is a prerequisite for regulating GHG standards under the CAA if not preempted by separate climate legislation. In 2009, EPA issued a related proposed rule jointly with NHTSA to regulate light-duty vehicle GHG emissions under the CAA, where the GHG emissions standard translates into CAFE standards for MY 2012-2016 passenger vehicles and light duty trucks. [17]

- *California Greenhouse-Gas Waiver Request (2008-2009)*. The California Air Resources Board requested a waiver of pre-emption under the Clean Air Act for regulating GHG emissions of certain new motor vehicles beginning with model year 2009. The waiver would have allowed California to issue its own GHG emissions regulations for vehicles. In 2008, EPA subsequently denied the waiver stating that California did not have "compelling and extraordinary conditions" required for issuing its own GHG standard. In a letter prior to the official notice, EPA noted that the climate change "challenge is not exclusive or unique to California and differs in a basic way from the previous local and regional air pollution problems addressed in prior waivers [given to California]." However, under the new administration, EPA reconsidered its previous decision and granted California the waiver on June 30, 2009.[18] Prior to granting the waiver, a number of other states had announced plans to adopt the California vehicle GHG standard; however, the Obama administration had also announced plans for a national GHG standard for light duty vehicles through 2016 that were consistent with the California standard.[19] As noted in the

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[15] See Section III.G of EPA's ANPR, as well as the Technical Support Document on Benefits of Reducing GHG Emissions, U.S. Environmental Protection Agency, June 12, 2008, www.regulations.gov (U.S. EPA, 2008).

[16] Endangerment and Cause or Contribute Findings for Greenhouse Gases under the Clean Air Act, signed December 7, 2009, published December 15, 2009, effective January 14, 2010. Federal Register (Docket ID No. EPA-HQ-OAR-2009-0171, www.regulations.gov). U.S. Environmental Protection Agency, Proposed Endangerment and Cause or Contribute Findings for Greenhouse Gases under the Clean Air Act, signed April 17, 2009, published April 24, 2009 in the Federal Register (Docket ID No. EPA-HQ-OAR-2009-0171, www.regulations.gov). The finding and Technical Support Document are also available at http://epa.gov/climatechange/endangerment.html.

[17] The proposed rule used the same marginal benefit value used in the final DOE beverage machine standard discussed above, as well as the same range of values for sensitivity analysis. Environmental Protection Agency, 40 CFR Parts 86 and 600, Department of Transportation National Highway Traffic Safety Administration, 49 CFR Parts 531, 533, 537, Proposed Rulemaking To Establish Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; Proposed Rule, Federal Register, Vol. 74, No. 186, September 28, 2009, pp. 49454-49789. Also see http://www.epa.gov/oms/climate/regulations.htm.

[18] http://www.epa.gov/OMS/ca-waiver.htm.

[19] http://www.epa.gov/OMS/climate/regulations/420f09028.htm.

CAA discussion above, a proposed rule for the national vehicles emissions standard was issued and received public comment.

Other domestic policies. Climate change impacts information was also considered in other domestic policy decisions.

- *Listing of threatened or endangered species (2008)*. The U.S. Department of Interior issued an interim rule in May of 2008 that listed the polar bear as a threatened species under the Endangered Species Act (ESA) due to the observed and expected continued loss of sea ice habitat.[20] The department later issued a special rule under ESA revising the earlier listing rule such that "any incidental take of polar bears that results from activities that occur outside of the current range of the species is not a prohibited act under the ESA." In a corresponding press release, the department clarified that statement with the following more extensive statement: "Based on the extensive analysis associated with the polar bear listing rule it has been determined that activities and federal actions outside Alaska do not currently show a causal connection impacting individual polar bears. Therefore, no consultation is warranted at this time for any such activities and actions. This provision ensures that the ESA is not used inappropriately to regulate GHG emissions."[21]
- *Consideration in new and existing facility approval (2008-2009)*. In the last days of President Bush's administration, EPA issued an interpretive memo that GHG emissions cannot be considered by federal officials reviewing permit requests for new power plants because GHG emissions are still not regulated under the CAA.[22] President Obama's administration granted a petition and decided to reconsider this position.[23] In September 2009, EPA released a proposed rule under the CAA for comment that proposes GHG thresholds for new and existing industrial facilities above which permits are required that demonstrate use of the best available control technologies and energy efficiency measures to minimize GHG emissions.[24]

International negotiations. The United Nations Framework Convention on Climate Change (UNFCCC) states as its ultimate objective the stabilization of atmospheric GHG concentrations at a level that would prevent dangerous interference with the climate

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[20] http://www.doi.gov/issues/polar_bears.html

[21] "New Rule Unifies Domestic and International Conservation Laws to Manage Polar Bear," U.S. Fish and Wildlife Service, News Release, December 11, 2008, http://www.fws.gov/news/newsreleases/showNews.cfm?newsId=27A58FDE-922A-2B50-ED394D030EE543BD, accessed 1-8-09.

[22] Stephen L. Johnson memo, December 18, 2008, http://www.epa.gov/nsr/documents/psd_interpretive_memo_12.18.08.pdf.

[23] Lisa P. Jackson letter to the Sierra Club, February 17, 2009, http://www.epa.gov/air/nsr/guidance.html. In related activity, EPA's Region 9 office recently requested remand of the Prevention of Significant Deterioration (PSD) permit issued under the previous administration for a new 1500 MW New Mexico coal-fired power plant to allow for reconsideration (Desert Rock Energy Facility Motion for Voluntary Remand, April 27, 2009, http://www.epa.gov/region/air/permit/desert-rock/).

[24] Environmental Protection Agency, Prevention of Significant Deterioration and Title V Greenhouse Gas Tailoring Rule, September 30, 2009, http://www.epa.gov/NSR/actions.html#sep09.

system. Deciding what this level should be, and when and how it should be achieved, requires scientific knowledge about projected impacts associated with different GHG concentration pathways, as well as judgment and policy decisions regarding costs to achieve different targets and risk tolerance. There is currently no scientific or global policy consensus on the stabilization level that satisfies this objective. However, a recent statement joint statement from delegates at the UNFCCC's 15th Conference of Parties in Copenhagen, Denmark suggests greater coalescing:

> *"We agree that deep cuts in global emissions are required according to science, and as documented by the IPCC Fourth Assessment Report with a view to reduce global emissions so as to hold the increase in global temperature below 2 degrees Celsius, and take action to meet this objective consistent with science and on the basis of equity. We should cooperate in achieving the peaking of global and national emissions as soon as possible…and that a low-emission development strategy is indispensable to sustainable development."*[25]

The Kyoto Protocol to the UNFCCC was negotiated with only a general sense of how its interim targets were steps towards the UNFCCC stabilization objective. Current international negotiations regarding the appropriate global magnitude and timing of emissions reductions are driven by both perceived potential impacts and the expected costs of reductions. For instance, in 2007, the European Commission issued a communiqué stating that "[b]y 2050 global emissions must be reduced by up to 50 percent compared to 1990, implying reductions in developed countries of 60-80 percent by 2050…," with developing countries also needing to significantly reduce emissions by an unspecified amount. The Commission's objective was "…to limit global average temperature increase to less than 2°C compared to pre-industrial levels…, [which would] limit the impacts of climate change and the likelihood of massive and irreversible disruptions of the global ecosystem."[26] In July 2009, the G-8 countries, including the U.S., appear to have endorsed this objective.[27] Of course, both the cumulative potential impacts and their distribution are relevant information for the negotiations, as are the total level of emissions, the distribution of emissions, and the cost of reductions, as is the total and distribution of emissions and costs.

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[25] Copenhagen Accord (http://unfccc.int/meetings/cop_15/items/5257.php).

[26] Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions – "Limiting global climate change to 2 degrees Celsius - The way ahead for 2020 and beyond," January 10, 2007, http://ec.europa.eu/environment/climat/future_action.htm (accessed January 21, 2009).

[27] White House Press Release, July, 9, 2009, Meeting the International Clean Energy and Climate Change Challenges, http://www.whitehouse.gov/the_press_office/Fact-Sheet-Meeting-the-International-Clean-Energy-and-Climate-Change-Challenges/. Some specifics are absent in the press release, such as the base years for determining emissions reductions and the maximum level of acceptable climate change.

3. Information and impacts analyses requirements

What impacts information is needed to support the types of decisions described in the previous section? In answering this question it is helpful to work through two steps. First, it is useful to characterize the problem statements (i.e., the objectives of the decisions) and how impacts information is used. A different level and type of information is needed in each case, and the application of the information varies. The second step is to think about the scientific nature of the problem being evaluated and the relevant economic principles that follow. The results from the two steps define the scope of the information needed and the analyses required.

Types of decisions

Each of the various decisions in Section 2 can be characterized as having one of the following objectives: determining if a threat exists, setting a technological standard, mandating a pathway for emissions, or evaluating a predefined policy (Table 1). Each is discussed below.

- *Determining if there is a threat.* In this case, the objective is to determine if there is a threat significant enough to merit further action. This category can be further refined into (i) *determining if there is a potential threat* and (ii) *determining if there is a threat that justifies regulation*. The Supreme Court decision falls into the former, while the actual finding on endangerment, which is in EPA's hands and would trigger a regulatory process under the Clean Air Act, falls into the latter. The California waiver request, DOI's listing of the polar bear, and EPA's consideration of GHGs in new facility approval also fall into the latter category. Impacts information is used to determine if additional action should be considered.[28] These types of decisions primarily require biophysical information on potential climate change and ecosystem and anthropogenic impacts, but do not call for precision in the information like some of the other types of decisions. For example, demonstrating the crossing of a quantitative threshold or specifying a monetized effect is not required. Furthermore, point estimates (versus distributions or ranges) can be sufficient for judging if further consideration is merited.
- *Setting a technological standard.* The objective is to mandate a standard for technology, and specific impacts data is used in defining the level. The NHTSA and DOE decisions described in Section 2 for setting minimum vehicle and appliance efficiency requirements are examples. In this setting, monetized impacts information is part of the calculus of determining the specific level of the standard. Specifically, monetary estimates for the resulting changes in impacts are used in a cost-benefit analysis to identify a regulatory option that either maximizes net monetary benefits by equating

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[28] If EPA decides to consider GHG emissions in the approval of new facilities, the agency will be confronted by a new decision: how to include consideration. This decision is similar to the decision of setting a technological standard that is discussed further below.

marginal benefits to marginal costs, or evaluates alternatives based on the ratio of benefits to costs.

Table 1. Decision types and characteristics of impacts information requirements.

		Types of impacts information						
Type of decision	**Decision process**	**Qualitative/ quantitative**	**Nonmonetary/ monetary**	**Observed/ projected**	**Domestic/ Global**	**Incremental/ non-incremental**	**Point/ distribution**	**Information requirements**
Determining if there is a potential threat	U.S. Supreme Court ruling	Primarily qualitative relationships	Primarily nonmonetary information	Primarily observed impacts	Domestic	Non-incremental	Distribution	Lowest
	U.S. 9th Circuit Court ruling				Ambiguous	Incremental		
	New facility approval*				Ambiguous	Incremental		
Determining if there is a threat that justifies regulation	EPA endangerment ruling	increasingly quantitative ↓	increasingly monetary ↓	increasingly future looking ↓	Domestic	Non-incremental		↓
	California GHG waiver request				Domestic	Non-incremental		
	Threatened species listing of the polar bear				Global**	Non-incremental		
Evaluating a predefined policy	Twenty-in-Ten				Global**	Incremental		
	Renewable Fuels Standard				Global**	Incremental		
Mandating a pathway for emissions	Clean Air Act				Global**	Ambiguous		
	Legislative proposals				Global**	Non-incremental		
	International negotiations				Global**	Non-incremental		
Setting a technological standard	CAFE standards	Quantitative relationships	Monetary information	Projected impacts	Global**	Incremental	Point	Highest
	Appliance efficiency standards				Global**	Incremental		

** This refers to EPA's deliberations on whether to consider GHG emissions in the approval of new facilities. With its proposed rule on GHGs and industrial source permitting, the agency is confronting a new decision—how to consider emissions. This decision is similar to the decision of setting a technological standard.*
*** Global information for welfare maximizing decision-making, but domestic information is informative.*

- *Mandating a pathway for emissions.* The objective in this case is to define a permissible GHG emissions pathway through time. Impacts information would be useful to evaluate the implications of alternative pathways. Legislative proposals, the Clean Air Act, and international negotiations have this objective. Under the Clean Air Act traditionally, science based health and ecosystem end points have defined the permissible criteria pollutant emissions levels, such as mortality and morbidity rates, irrespective of costs. However, GHG emissions control proposals to date have not been defined by specific end points. This is not surprising given the degree of uncertainty associated with particular impacts. However, prescribing an emissions pathway implicitly defines some level of acceptable risk of climate change impacts. Each individual emissions pathway generates a probability distribution over specific outcomes. The choice of a specific emissions pathway implies a selection of the corresponding level of risk. This type of decision therefore requires risk information, i.e., characterizations of the range of potential impacts and ideally both the magnitude and probability of impacts. The information could be both quantitative and more qualitative where the sign alone (i.e., direction of change) can be useful information.
- *Evaluating a predefined policy.* In this case, a standard is mandated by Congress or the president and impacts information is used simply for evaluating the climate change benefits of the chosen policy. The Renewable Fuels Standard and 20-in-10 policy are examples of this type of process. Of course, impacts information of some type may have been considered in developing the mandate, which is akin to mandating a pathway for emissions as described above.

The following categories of impacts information that could be needed by each type of decision: qualitative and quantitative, non-monetary and monetary, observed (i.e. historical) and projected, domestic and global, incremental and non-incremental, and point estimates and distributions (or simply ranges) of estimates (Table 1).[29] Not all decisions require every type of information. For instance, the Supreme Court decision can rely more on observed non-monetary information, in particular quantified biophysical impacts and more qualitative information (e.g., the direction of change), while non-climate policies with incremental emissions implications (relative to global emissions), such as the RFS, need not be as concerned about changes in the likelihood of catastrophic impacts (such as a slowing of the Atlantic thermohaline circulation). The table also lists the decisions by objective type in an order representative of increasing demand for information precision. For instance, standard setting has a much higher information requirement bar than threat determination. Global versus domestic and incremental versus non-incremental impacts

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[29] Non-monetary impacts are defined here to include quantified biophysical, social and cultural impacts, where biophysical is broadly defined to include all physical effects (e.g., atmospheric, oceanic, hydrologic, weather, ecosystem, and human health). Monetary impacts include monetary estimates of market and non-market effects, where the former includes things like production and infrastructure values, and the latter includes willingness to pay estimates for outdoor recreation, environmental services, species effects, and natural amenities.

information requirements are discussed below with respect to the nature of GHGs and the state of the art respectively.

The physical and economic nature of greenhouse gases and climate change

Understanding the physical nature of the environmental issue is essential for two reasons: properly characterizing and addressing the social problem, and identifying the appropriate information needed for decision-making. Environmental concerns in general are issues of externalities and public goods, where the actions of individuals or entities do not take into account the full societal costs and benefits of their actions, leaving others involuntarily affected. This section discusses the scientific nature of GHGs and the economic principles relevant to climate change policies that follow.

Physical nature of GHGs and climate change. GHG emissions are different from traditionally regulated emissions, such as those regulated under the Clean Air Act, in several important ways. First, GHGs have global implications. Unlike criteria air pollutants, GHGs are chemically stable and therefore mix well in the atmosphere such that they can affect climate globally (IPCC WGI, 2007). Where criteria pollutants tend to have health and environmental impacts close to their emission sources, each unit of GHG emissions, regardless of the location of its source in the world, affects regional climates throughout the world; and therefore, impacts regional biophysical systems. Working Group II of the IPCC notes that "[o]bservational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases" (IPCC WGII, 2007).

Second, because of their long atmospheric lifetimes and inertia in the climate system, GHGs have very long-run implications, such that emissions today accumulate in the atmosphere, combining with past and future emissions, and thereby affecting future climate for decades to centuries or longer. This also means that there is already a degree of commitment to future climate change given past and current GHG emissions, and likewise a delay in the climate and impacts response to GHG reductions.

Third, projected changes in climate could result in or contribute to impacts that exceed thresholds in the dynamics of geophysical and biophysical systems and are irreversible on the timescale of centuries or longer. For example, "[s]ome large-scale climate events have the potential to cause very large impacts, especially after the 21st century," including "[v]ery large sea-level rises that would result from widespread deglaciation of Greenland and West Antarctic ice sheets [and] imply major changes in coastlines and ecosystems, and inundation of low-lying areas, with greatest effects in river deltas" (IPCC WGII, 2007). The resilience of many ecosystems is also likely to be exceeded this century by "…an unprecedented combination of climate change, associated disturbances (e.g., flooding, drought, wildfire, insects, ocean acidification), and other global change drivers (e.g., land use change, pollution, over-exploitation of resources)" (IPCC WGII, 2007). While scientists are still uncertain about the probability of any given threshold event occurring in a particular year, the significant nature of such events still provides cause for concern among many researchers and policymakers regarding the potential effects of climate change.

Fourth, given physical inertia in the climate system, as well as inertia in the economic system, substantially altering climate from projected business-as-usual conditions will require large GHG emissions mitigation beyond the mitigation opportunities within any one country (IPCC WGIII, 2007).

Finally, the impacts of climate change are inherently uncertain. Uncertainties exist all along the casual chain—from global socioeconomic projections, to emissions, to climate and atmospheric responses, to biophysical responses, to impacts and adaptation reactions, and in the feedbacks back to the socioeconomic system.

Economic principles. A number of fundamental economic principles follow directly from the scientific qualities of GHGs and climate change. As is the case with other pollutants, anthropogenic climate change results from a market failure: emitters of GHG emissions fail to take into account the impacts of these emissions on others. When unaccounted for, these impacts are referred to as externalities. However, GHG emissions are different from most air pollutants. Because GHGs mix well in the atmosphere, they are a global pollutant, and because GHGs are long-lived in the atmosphere, they are a stock pollutant (i.e., they accumulate in the atmosphere and increase atmospheric concentrations). As a result, GHGs have global and inter-generational externalities: a ton of GHG emitted from any source in any location can cause impacts throughout the globe—both to the source country and abroad—and can impact multiple generations. Given the scope of the externalities, climate change can be characterized as a global and inter-generational public goods problem.

Public goods are defined in economics by two key properties: non-rivalry and non-excludability (Samuelson, 1955). In the climate change context, non-rivalry means that the use or consumption of the public good by one country or generation does not reduce the availability of that good to another country or generation. In other words, the level of benefits received in North America from reduced global warming is not affected by the level of benefits received in Africa. Non-excludability means that no one country or generation can be excluded from being affected by changes in climate. The implication is that a GHG emissions reduction anywhere will have the same global and temporal benefit.

How much of the climate change public good should be provided? In other words, how much anthropogenic climate change should be allowed? According to the principles of welfare economics, we should seek the level that maximizes net societal benefits (i.e. that is economically efficient). Maximizing net societal benefits requires internalizing all societal benefits and costs—both direct private benefits and costs as well as all externalities. Therefore, the efficient spatial and temporal scope is determined by the scope of the externalities, not by geopolitical boundaries or the lifespan of current decision-makers.

The implication is that domestic policies can only be economically efficient if they account for the global and long-run implications of their effects on GHGs. Conceptually, this outcome would require that each country mitigate up to the point where their domestic marginal cost equals the global marginal benefit (Nordhaus, 2006).[30] The use of global marginal benefits would internalize the global externalities of reducing a unit of emissions and therefore correct for the spatial market failure. Internalizing the generational externality requires consideration of the effects on multiple generations, including those well beyond current living generations. Therefore, the benefits of an emissions reduction should include the present value of the stream of climate change impacts for the life of the GHG and any subsequent climate system inertia consequences.[31] This raises the issue of discounting. How should public decision-makers weigh future effects in current decisions? This topic is addressed following additional discussion of domestic decisions.

Individual countries might consider focusing solely on their domestic marginal benefit of emissions reductions.[32] In this case, a country equates its domestic marginal benefit to its domestic marginal cost of emissions reductions. The mitigation undertaken would be lower than if all the international externalities had been internalized since the domestic marginal benefits felt directly within a county's borders are only a fraction of the global marginal benefits. The mitigation would generate domestic benefits, as well as positive externalities for other countries. However, there would continue to be a market failure with decisions based on domestic marginal benefits because the remaining domestic emissions would be produced without accounting for their full cost to society, i.e., their international intertemporal effects. If all countries internalized the full cost of their emissions, the world as a whole would be better off than if each country internalized only the domestic externalities of their emissions in their decisions. Moreover, in addition to being inefficient, there is expected to be little appreciable mitigation of GHGs globally if every country considered GHG mitigation from its domestic marginal benefits perspective, and therefore little resulting response in the climate (Nordhaus, 1995).

An additional complication for evaluating GHG reduction benefits is that domestic decisions may affect the level of emissions in other countries. Emissions internationally could be affected by either international climate policy reactions to the domestic policy (such as reciprocal adoption of a mitigation policy) and/or production reactions (such as increased international production in response to higher U.S. production costs). A failure to account for these indirect feedback effects could result in biased estimates of changes in projected impacts to the domestic policy because the net climate change response, and the benefits realized domestically and globally, are a function of the net change in *global* emissions.

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[30] Uncertainties can complicate actual application of this economic efficiency rule (discussed later). Nonetheless, the principle is still sound.

[31] For example, thermal inertia associated with the time lag in the response of oceans to atmospheric temperature changes. It is because of this inertia, and the atmospheric lifetime of greenhouse gases, that global average temperature and sea level will continue to rise even if greenhouse gases emissions are stabilized (Meehl *et al.*, 2005).

[32] NHTSA and DOE followed this approach in their proposed 2008 CAFE and appliance efficiency rulemakings.

As discussed in Section 4, actually identifying the optimal level of provision of the climate public good is problematic on its own. Coordinating autonomous decision-makers to achieve that level is an additional significant challenge. Economic game theory can be helpful in thinking about the strategic behavior of countries with respect to climate policy. Achieving a significant reduction in projected climate change is a type of assurance game.[33] International coordination is required because it is technically infeasible for individual regions to reach the provision level on their own with mitigation within their own borders. Essentially, there is a provision threshold that must be met to assure that the benefit is provided. With respect to climate change, the cooperative threshold could be a temperature level above which there are impacts deemed unacceptable to society or a geophysical threshold associated with a catastrophic event such as the collapse of the West Antarctic Ice Sheet (both of which could be implied by the UNFCCC ultimate objective to prevent dangerous anthropogenic interference). Each of these examples is associated with implied atmospheric concentrations of GHGs, permissible global emissions, and therefore global emissions reductions from a reference case. These cases can be described as having a threshold that must be met for the public good to be provided, or a loss avoided.

The benefits of the climate change mitigation assurance game would be defined by impacts assessments, which could characterize the potential risks and the required global responses for reducing them by varying degrees. Decision-makers could then weigh the information in defining the provision threshold associated with unacceptable impacts.[34] Impacts information is essential to characterizing the changes in risk and associated cooperative thresholds.

Because there is a minimum amount of coordination required to provide the good in an assurance game, free riding incentives are diminished. While the benefits and costs of providing the public good are not evenly distributed across countries, there is an increased incentive to participate for each region that receives a benefit, where the benefit includes direct benefits as well as value for international concerns—such as national security, humanitarian, potential use value, and existence values. In a prisoner's dilemma game, the dominant strategy is to not cooperate. That is not the case in the assurance game. Instead, participants are strategically inclined to act as a group—either for full cooperation or no cooperation at all. Furthermore, participation is self-enforcing, as each participant will want to participate and continue to participate if others participate. Finally, it is economically rational for participants (regions) to reveal their plans for emissions reductions to other participants to encourage cooperation. The experimental economics

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[33] For a good discussion of assurance games, see Cornes and Sandler (1996) and Sandler (1997).

[34] Avoided climate change impacts are not the only potential benefits of GHG mitigation. For instance, there may also be benefits associated with air quality, energy use, technological change, and future economic competitiveness.

literature has validated these points in finding increased participation in actual decisions for providing public goods with minimum cooperative participation requirements.[35]

While an assurance game does not guarantee provision of the public good, it increases the strategic incentives for participation, revelation, and sustained commitment. The resulting environment is also conducive to coordination, such as coordinating the least-cost form of group participation via, for example, cost-effective financial or technological transfers that equates the marginal cost of participation across countries.

Finally, given the substantial emissions and climate uncertainties, there is significant uncertainty in quantifying many aspects of climate change and climate change impacts, including those associated with characterizing thresholds and the risk of exceeding them (IPCC WGI, WGII, WGIII, 2007; U.S. CBO, 2005). Large uncertainty has bearing on valuation, discounting, and the overall decision approach. For instance, society values reductions in risk, as reflected in different rates of return for high and low risk financial assets. However, deterministic estimates of the value of climate change impacts do not reflect the uncertainty and risk related to climate change, or attitudes towards risk, and therefore ignore the value of reducing risk (i.e. the risk premium). As a result, deterministic estimates underestimate the benefits of emissions reductions, which could be substantial for risks like potential catastrophic events (Weitzman, 2007, 2009).

The large degree of uncertainty also affects the discounting of impacts. Discounting is used in the aggregation of benefits or costs over time and the discount rate reflects trade-offs between current and future consumption or private investment. Activities that increase (decrease) emissions are very long-run investments in additional (avoided) impacts over a period of 100 years and longer. As a result, the valuation of impacts will be particularly sensitive to the discount rate used.

Unfortunately, current markets fail to capture the long-run returns associated with changes in GHG emissions. Climate change investments should be compared to similar investments via the discount rate. However, investments in climate change represent longer-term investments than those represented in financial markets. There is also a potential for significant impacts from climate change, where the exact timing and magnitude of these impacts are unknown and may be irreversible. Overall, the long time horizon and potential for large impacts imply a more uncertain investment than represented in current markets, and therefore greater potential for low economic growth conditions.

As a result, it is practical to consider lower interest rates than current market rates based solely on economic efficiency arguments.[36] A three percent discount rate represents observed interest rates from long-term *intra*-generational (within generation) investments

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[35] E.g., Bagnoli and Lipman (1989); Isaac et al. (1989); Bagnoli and McKee (1991); Rose et al. (2002); Rondeau et al. (2005).

[36] Intergenerational equity arguments are frequently offered as justification for low (even zero) discount rates (see, for example, Portney and Weyant, 1999). The discussion here considers only economic efficiency.

(net of risk premiums). With inter-generational investments, the horizon is longer and the uncertainty greater, including the potential for climate damages to economic growth. Rates of three percent or lower are consistent with conditions associated with the even longer-run uncertainty in economic growth, as well as the consumption effects of climate change impacts and the risk of high impact climate damages (which could reduce or reverse economic growth). Intra-generational consumption trade-offs, which are relevant because monetary estimates of the impacts of climate change are primarily consumption effects, are commonly valued at three percent.[37]

Given the extra long time horizon, it is also practical to consider that economic growth is likely to change over time, and therefore so will the discount rate. Uncertain interest rates would be practical to consider as well with modeling of uncertainty in economic growth and other parameters. In this context, the imputed (or effective) future discount rates will decline over time as investment uncertainty and risk increase and alternative futures with low discount rates dominate expected net present value calculations.[38] However, applications with uncertain discount rates should take steps to ensure consistency between the discount rate trajectories and future economic growth.[39]

Overall, in situations with large uncertainties, such as climate change and climate change impacts, economics recommends an iterative risk management framework as being appropriate for guiding policy (Manne and Richels, 1992; IPCC WGIII, 2007, Chapter 3). In such a framework, decisions are based on a policy defined "acceptable" level of risk and the course is revisited and revised as new information becomes available. This approach stands in marked contrast to cost-benefit analysis designed to identify an optimal decision and outcome or net benefit evaluations designed to identify net positive alternatives. The

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[37] U.S. CBO (2005, p. 20) discusses using the rate of return from long-term government bonds as a rough proxy for very-long-term rates of return, noting that "funds continuously reinvested in 10-year U.S. Treasury bonds from 1789 to the present would have earned an average inflation-adjusted return of slightly more than 3 percent a year." U.S. EPA (2000) recommends a consumption rate of interest of two to three percent based on historical rates of return for relatively risk-free investments, such as U.S. Treasury securities (adjusted for taxes and inflation). U.S. OMB (2003) uses three percent to represent the rate at which society discounts future intra-generational consumption flows to their present value. The rate is based on the real rate of return on long-term government debt over the last thirty years of 3.1 percent. While U.S. EPA (2000) and U.S. OMB (2003) identify inter-generational discount rates of 1 percent to 3 percent (0.5 percent to 3 percent for EPA), they require that analysis also be performed with 3 percent and 7 percent discount rates. Rates of three percent and lower are consistent with intergenerational issues, as discussed in this paper, while seven percent is inconsistent with these issues and not readily supportable. Note that EPA and OMB are in the process of revising their analytical guidance, including their discounting sections.

[38] This approach to discounting has been shown to be conceptually appropriate for greenhouse gas (GHG) emissions-related investments with extremely long-run implications and is not subject to time inconsistency problems (Newell and Pizer, 2001, 2003; Weitzman, 1999; Pearce, 2002). Furthermore, it has been shown that constant discounting can substantially undervalue the future (Newell and Pizer, 2001). For example, a constant 7 percent rate could undervalue net present benefits by 95 percent or 21 percent depending on the model of interest rate uncertainty over time and a starting rate of 7 percent, and 700 percent or 440 percent for a starting rate of 4 percent.

[39] Specifically, the discount rate should be a function of economic growth. Independent estimates of uncertain discount rates and economic growth projections would likely be inconsistent.

next section discusses the state of climate change information, including uncertainties, and describes the resulting complications for decision-making.

4. State of knowledge for incremental and non-incremental decisions

Knowing what data and analyses you need is necessary, but not sufficient. We must also understand the types of information available to the decision process in order to design more robust decisions. This section discusses the state of impacts related information for supporting policies with incremental (small) and non-incremental (large) global GHG emissions implications. In so doing, the section stresses the importance of acknowledging the difference between policies with incremental and non-incremental effects. Policy questions about the cost of inaction, economically optimal mitigation policies, or the GHG benefits of particular legislative proposals are concerned with large changes in global emissions. Many non-climate policies, such as CAFE, RFS, and appliance efficiency standards, have relatively small net effects on global GHG emissions. Current analytical capabilities are better suited to analysis of incremental emissions changes. In addition to this primary issue, the discussion also highlights other fundamental issues and challenges for decision-makers: comparing marginal benefits and marginal costs, partial characterizations of uncertainty, risk valuation, information inconsistencies, and non-monetary information. First, we discuss some common issues for both incremental and non-incremental impacts analyses.

Overall, impacts information is limited, with partial geographic and sector coverage. There are significant fundamental data limitations, especially climate and biophysical data, which

Box 1. Categories of uncertainty (for each, there are historical and projected uncertainties)

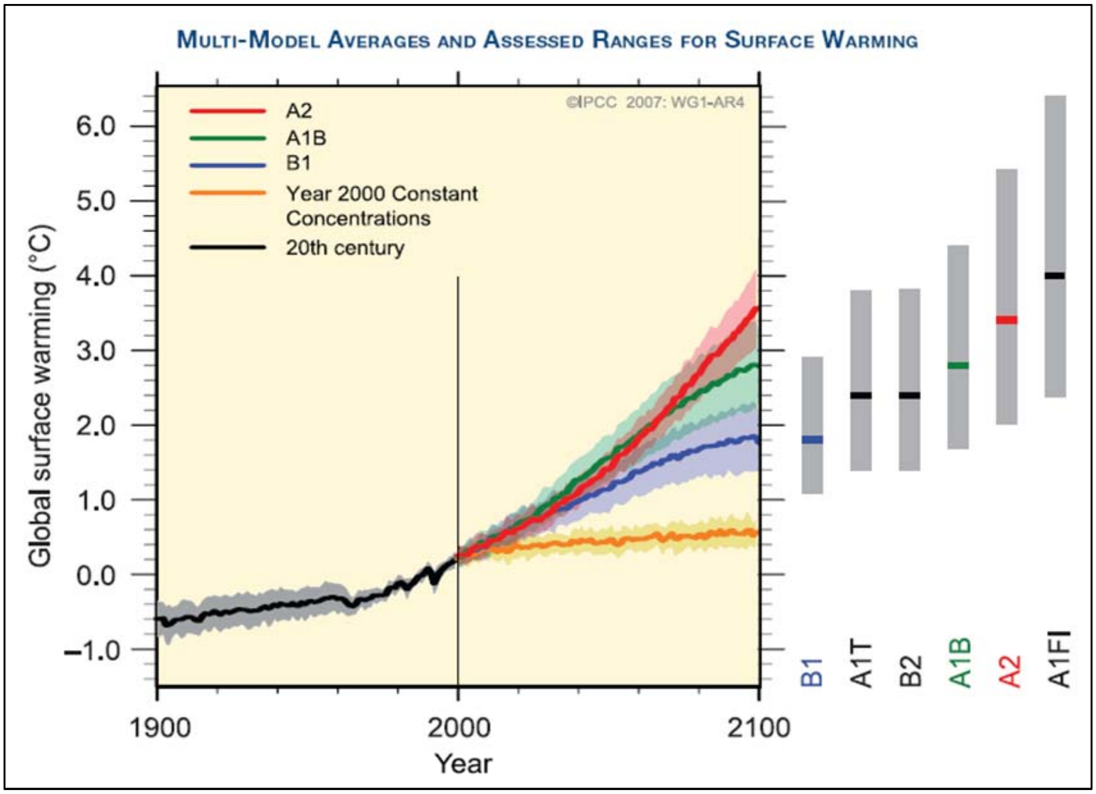
- Socioeconomic, e.g.,
  - Demographics – size, composition, and location of population
  - Income – wealth levels and rates of per capita growth
  - Economic elasticities – dictate responsiveness to changes in relative prices and income
  - Preferences – defines demand for goods and services, domestic and imported
  - Technological – e.g., costs, R&D, diffusion, current vs. new technology, rates of change, market responsiveness
  - Resource endowment availability and productivity
- Emissions and sequestration
- Biophysical response, e.g.,
  - Climate
  - Carbon cycle
  - Nitrogen cycle
  - Biogeophysical
  - Terrestrial ecosystem
- Impacts – exposure, adaptive capacity and response, net effect, feedbacks to economic and biophysical dynamics
- Policy – climate and non-climate (e.g., air quality, energy, development, technology)

are essential inputs into economic analyses. Impacts information will only evolve as quickly as the data. Second, uncertainties abound, from emissions through to net impacts. Box 1 provides a high-level list of uncertainty categories. Given the temporal and spatial scope and that we are considering potential biophysical and economic outcomes that extend well beyond observations, there are limits to how much we will ever be able to resolve the uncertainty. For instance, it is impossible to forecast the economy in 2100 with accuracy, or to know when exactly the West Antarctic Ice Sheet will collapse. Even probabilistic analysis and expected utility theory, which are very appealing and appropriate for analyzing climate change, are challenged by data constraints in estimating distributions. So, what do we know?

Policies with incremental GHG emissions changes

When concerned about incremental global emissions reductions (increases), it is reasonable to ask, is there a measurable benefit (cost)? This question can be broken down into is there an incremental climate signal, and is there a value? Current IPCC climate change projections (Figure 1) suggest that there is about a 1 degree Celsius uncertainty range by 2100 for any emissions scenario. The true uncertainty range is likely even larger (discussed later). This suggests that the impacts of marginal emissions changes would be lost in the noise and not produce a measurable climate signal. In other words, we could not say that a marginal emissions reduction will result in an *x* degree reduction in global

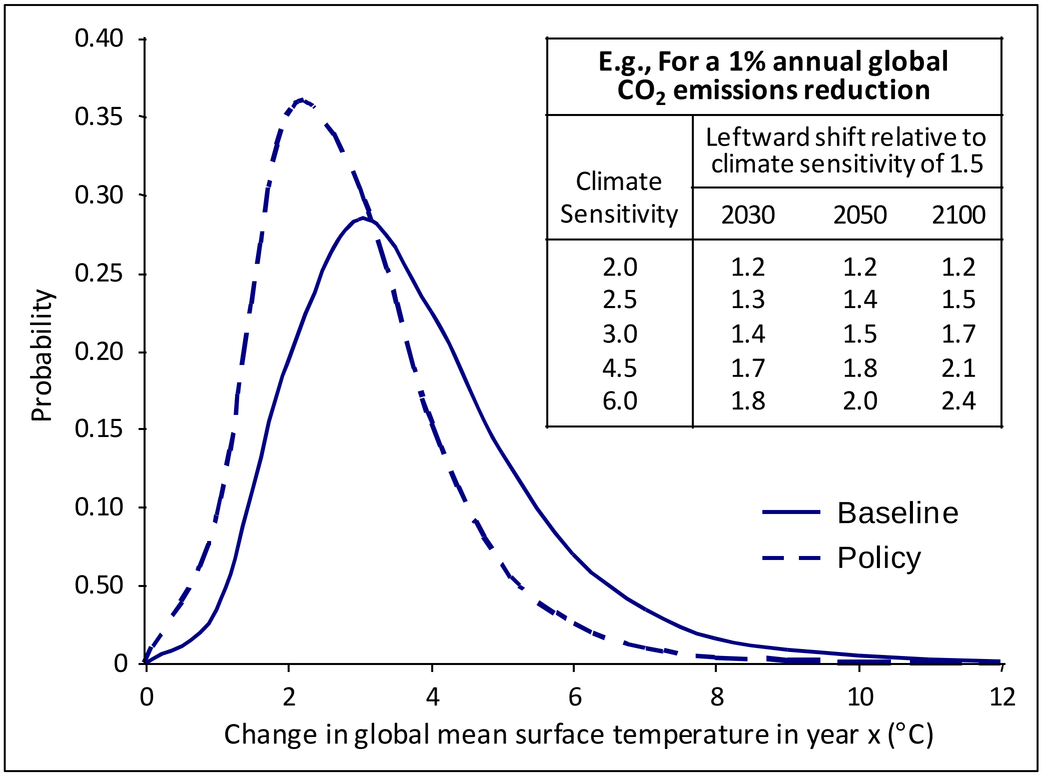
Figure 1. Historical and Projected Global Mean Surface Temperatures (*Source: IPCC WGI 2007)*



average temperature in year *y* with any degree of certitude. However, given the uncertainties, we should be looking at a different metric. We should instead look for the climate signal in the likelihood of potential climate change: will a marginal emissions reduction result in a decrease in the probability of an increase in global average temperature of *x* degrees by year *y*? Figure 2 provides an illustration of this type of signal. Under a policy, does the distribution for global mean surface temperature shift left and become more compact, with the right tail shifting further than the left tail?

Current capabilities can provide this type of information. For instance, the embedded table in Figure 2 presents results from a straightforward evaluation of global average surface temperature responses under alternative climate sensitivities to a small annual reduction in global CO_2 emissions (1 percent per year).[40] The reduction in projected temperature is largest for a climate sensitivity of 6, and smallest for a climate sensitivity of 1.5. Given the right skewed probability distribution of climate sensitivity,[41] ceteris paribus, the distribution of projected temperatures is therefore shifting to the left and becoming more

Figure 2. Illustrative reduction in the probability of higher global mean surface temperatures in some outyear x.



E.g., For a 1% annual global CO_2 emissions reduction

Climate Sensitivity	Leftward shift relative to climate sensitivity of 1.5		
	2030	2050	2100
2.0	1.2	1.2	1.2
2.5	1.3	1.4	1.5
3.0	1.4	1.5	1.7
4.5	1.7	1.8	2.1
6.0	1.8	2.0	2.4

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[40] Calculations performed with the MAGICC model (Model for the Assessment of Greenhouse-gas Induced Climate Change, Wigley and Raper, 1992; Raper et al., 1996; Wigley and Raper, 2002) using the Clarke et al. (2007) baseline emissions for the MiniCAM model.

[41] The IPCC states that climate sensitivity is "likely" (> 66 percent probability) to be in the range of 2°C to 4.5°C and described 3°C as a "best estimate", which is the mode (or most frequent) value. The IPCC goes on to note that climate sensitivity is "very unlikely" (< 10 percent) to be less than 1.5°C and "values substantially higher than 4.5°C cannot be excluded." IPCC WGI (2007).

compact as the right end of the distribution shifts further than the left. Specifically, the leftward shift in the right-tail is nearly twice that in the left-tail in 2030, and the ratio increases in later years. In other words, the risk of higher temperatures is reduced, even if only just a bit, which has implications for the risk of impacts. Similar phenomena are at the heart of more sophisticated analysis of non-incremental emissions changes (e.g., den Elzen and van Vuuren, 2007). Therefore, a signal can be established. That leaves us with the value question.

Conceptually, for policies valuing incremental changes in net global emissions, we should consider a marginal value. The economics literature has been generating marginal value estimates for over a decade (see the meta analysis of Tol, 2008). These estimates are commonly referred to as the social cost of carbon (SCC). The SCC is the net present value of climate change impacts over 100 plus years of one additional net global ton of GHGs emitted to the atmosphere at a particular point in time. It is a theoretically appropriate metric for monetizing the benefits of incremental global GHG emissions reductions. Estimating the SCC requires global modeling frameworks with consistent integrated socioeconomics, emissions, climate change, and impacts. Current capability is limited to aggregated integrated models due to data limitations. Not surprisingly, when modeling the biophysical and economic systems of the globe for more than 100 years there are inherently large uncertainties.

Table 2. Marginal benefits estimates – e.g., summary of EPA estimates for changes in emissions in year 2007 and 2030 for 2 percent, 3 percent, and 7 percent discount rates (2006$) (*Source: U.S. EPA 2008)*

		~ 2%			~ 3%			~ 7%		
		Low	Central	High	Low	Central	High	Low	Central	High
Meta global	**2007**	-3	68	159	-4	40	106	n/a	n/a	n/a
	2030	-1	134	314	-2	78	209	n/a	n/a	n/a
FUND global	**2007**	-6	88	695	-6	17	132	-3	-1	5
	2030	-3	173	1372	-3	33	261	-1	0	11
FUND US	**2007**	0	4	16	0	1	5	0	0	0
	2030	0*	9	32	0*	2	11	0*	0*	0*

** USEPA (2008) notes that these estimates, if explicitly estimated, may be greater than zero, especially in later years. See USEPA (2008) for the full footnote.*

Table 2 provides estimates published by EPA in 2008 (U.S. EPA, 2008). These estimates are presented because the methods and estimates provide a useful illustration of uncertainties and many of the challenges and controversies associated with estimating the SCC. For a focused discussion of these issues and the most recent federal SCC estimates and their use, see Rose (2010). EPA undertook two analytical analyses and generated ranges of estimates for different discount rates and year of emissions change. The estimates include global values from a meta analysis of peer reviewed estimates that is a refinement of the Tol (2005, 2008) meta analyses, and a consistent set of domestic & global estimates using a single model that has published regularly in the peer reviewed literature (the "Climate

Framework for Uncertainty, Negotiation, and Distribution", i.e., FUND).[42] Global SCCs are all that currently exist in the peer reviewed literature.

The estimates are relevant for incremental policies off of a baseline projection without climate policies. They are not estimates of "optimal" marginal benefits, which would result from equating the marginal benefits and marginal costs of emissions reductions. See U.S. EPA (2008) for additional methodological details and a discussion of the estimates, including a comparison to Tol (2005), and guidance on application of the estimates.[43]

The few important general points are illustrated in Table 2. Note that these points are ubiquitous, in that they are applicable to the entire SCC literature, not just EPA's estimates. First, given uncertainties, ranges of SCC estimates are appropriate, based on alternative assumptions of key scientific and economic parameters, as well as models, where multiple models can provide more robust results than a single model. For instance, higher values are associated with higher climate sensitivities, higher projected emissions, slower economic growth per capita globally and regionally, and lower discount rates. Second, SCC estimates for emissions changes in subsequent years are higher due to a larger marginal effect on net damages. The IPCC suggests that the SCC increases 2 percent to 4 percent per annum (IPCC WGII, 2007, Chapter 20). Three percent was applied in Table 2. Other recent preliminary work using FUND with "central" assumptions produced average annual growth rates of 2.8 percent and 4 percent for the period 2005-2030.[44] Third, impacts from an emissions change today (~2007) are felt well into the future. This is made obvious by looking at results across discount rates. For example, in Table 2, the mean (central) FUND global value for an incremental change in 2007 emissions is \$88, \$17, or minus \$1/tCO_2 depending on whether the consumption discount rate is 2 percent, 3 percent, or 7 percent. The higher discount rate reduces the weight of future impacts to essentially zero—leaving only some near-term net beneficial effects (primarily due to crop CO_2 fertilization). Finally, the domestic estimates are only a small fraction of the global values, illustrating the relative extent of the international externalities of domestic emissions. Consistent with the earlier theoretical discussion of efficient public goods provision, a global SCC value therefore

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[42] The meta-analysis followed Tol (2008) and estimated Fisher-Tippett distributions for estimates that satisfied the following criteria: peer reviewed, from a more recent study (i.e., published after 1995), not equity weighted (i.e., regional aggregations were simple sums), and based on intergenerational consumption discount rates of approximately 2 percent and 3 percent. Fisher-Tippett was used because the sample was right-skewed with a thick right tail, and discount rates of 2 percent and 3 percent are consistent with EPA and OMB guidance on intergenerational discount rates (EPA, 2000; OMB, 2003). The FUND estimate ranges were generated from sensitivity analysis with respect to climate sensitivity, socio-economic and emissions baseline scenarios, and consumption discount rates of approximately 2 percent, 3 percent, and 7 percent. The low, central, and high columns in Table 2 are the 5th percentile, mean, and 95th percentile for the meta-analysis, while for FUND, they are the lowest, weighted average, and highest values from sensitivity analysis.

[43] Tol (2005) was used by the IPCC WGII (2007). Tol (2008) is an update of Tol (2005).

[44] Estimates generated by the author in collaboration with Richard Tol and David Anthoff. The SCC growth rate of 2.8 percent was generated using a consumption discount rate of 2 percent, while the SCC growth rate of 4 percent used a consumption discount rate of 3 percent. The FUND baseline and a climate sensitivity of three were used in deterministic scenarios for both.

internalizes more of the global and temporal externalities associated with GHG emissions/reductions in the U.S. or anywhere.

In addition to learning from the SCC estimates, it is also important to assess the estimates. First, there are substantial data deficiencies, because data are not available for every impacts category and region. As a result, transfer assumptions have to be used and more aggregate relationships are modeled (e.g., global mean temperature changes and national net agricultural impacts). Second, according to the IPCC, current estimates are "very likely" underestimated due to omitted impacts, including non-market values, threshold impacts (e.g., species extinction, catastrophic events), weather extremes (e.g., droughts, heavy rains, winds), and weather variability (IPCC WGII, 2007).[45] Furthermore, current estimates do not capture societal attitudes towards changes in risk, i.e., the value people have for reducing the likelihood of potential negative impacts (the risk premium). Current SCC modeling also does not capture global economic & social feedbacks, domestic willingness to pay for international impacts, and potential implications for other country action. Table 3 from EPA lists the included and omitted impacts categories for FUND, which is indicative of the state of the art.[46] Finally, non-CO_2 GHGs, such as nitrous oxide, methane, and fluorinated gases, will have different marginal values and growth rates over time than the marginal value of CO_2 emissions (IPCC WGII, 2007). Non-CO_2 GHGs have very different atmospheric lifetimes and radiative forcing effects, and therefore different climate and marginal impact implications. Using SCCs with carbon dioxide equivalent estimates of non-

Table 3. Lists of Impacts Modeled and Omitted from Current FUND Modeling *(Source: U.S. EPA, 2008)*

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

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

[46] The list of omitted FUND impacts is characterized as an initial, partial list.

CO_2 GHG emissions is practical for the moment. However, explicit estimates for the social cost of each non-CO_2 GHG will allow us to better capture the atmospheric and impacts trade-offs between gases.

Policies with non-incremental GHG emissions implications

Despite the fact that the SCC is well known, though not necessarily well understood (discussed below), and well represented in the literature, current estimates are not robust enough to guide the design of policies for significantly altering climate. A very different type of impacts analysis is required for evaluating and guiding non-incremental emissions changes.[47] Conceptually, as discussed previously, economic theory suggests mitigating emissions such that marginal benefits (i.e. the SCC) and marginal costs are equated over time. However, fundamental issues undermine this approach.

Comparing marginal benefits and marginal costs. The SCC is one type of published marginal value. Table 4 provides a representative sample of different types of marginal values. Unfortunately, differences between these marginal values are not well understood; and, as a result, they are inappropriately compared. There are two types of marginal benefit estimates in the literature—non-optimal and optimal. Table 2 presented estimates of the former that are marginal values off of a baseline (or reference) scenario.[48] Table 4 includes the baseline SCC cited by a number of petitioners in the NHTSA CAFE case that went before the U.S. 9th Circuit Court.[49] Optimal SCCs, on the other hand, are the result of attempting to find an optimal emission pathway that equates the marginal benefits and costs quantified in a model over time.

There are also two types of marginal cost estimates in Table 4—investment adders and mitigation. Investment adders are ad hoc per unit carbon dioxide emissions premiums applied to energy supply options by state energy providers. They are designed to force utilities to internalize the potential costs of future GHG regulations into current energy supply investment decisions. Marginal costs of mitigation represent the estimated expected private sector cost of the last unit of a future emissions reduction associated with a legislative proposal, emissions allowance trading market, or cost-effective global climate stabilization regime (given assumed projected baseline conditions, technologies, and biophysical and economic dynamics).

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[47] The line between incremental and non-incremental is currently not well-defined. Qualitatively, non-incremental changes are large enough to result in domestic and international biophysical and market transformations and feedbacks, and the net global emissions changes affect exposure to impacts and the likelihood of surpassing thresholds.

[48] There are also non-optimal SCC estimates off of stabilization pathways (e.g., U.K. Defra, 2007). Most SCC estimates in the literature are baseline SCCs. For purposes here, the important distinction is optimal vs. non-optimal.

[49] This value is only one of the meta analysis peer review means from Tol (2005).

It is impractical to use optimal SCCs or adders in a marginal benefit and cost comparison since the former has already considered marginal costs in its derivation and the later values are arbitrary and not indicative of an emissions reduction level or pathway.

Table 4. Other Representative Marginal GHG Values (2006\$/tCO_2)[50]

		2007	2015	2030
Baseline	CBD v. NHTSA comment [a]	25	31	49
Optimal	Nordhaus (2008) [b]	8	12	--
Investment adder	California Public Utilities Commission [c]	10	15	28
	Idaho Power Company [d]	15	22	47
Regional mitigation	Lieberman-McCain [e]	--	14	30
	Lieberman-Warner [f]	--	21	44
	Waxman-Markey [g]	--	13	27
	EU-ETS (futures contracts) [h]	\$27 (2008)	\$30 (2012)	--
	Deutsche Bank (forecast for 2008-2020) [i]	\$46 (2008-2012)	\$46 (2013-2020)	--
Global mitigation	3.4 W/m^2 stabilization (Clarke et al. 2007) [j]	--	--	54-122

a. *Center for Biological Diversity vs. National Highway Traffic Safety Administration, United States Court of Appeals for the Ninth Circuit, No. 06-71891, November 15, 2007. A number of petitioners referenced the Tol (2005) \$50/tC (1995 dollars for emissions changes circa 1995) meta analysis mean from peer reviewed studies. The value in the table has been converted to 2006 real dollars, carbon dioxide units, and adjusted for the different emissions years assuming a 3 percent growth rate (the midpoint of the IPCC WGII (2007) range of 2 percent to 4 percent).*

b. *Nordhaus (2008) provides optimal SCCs for 2005 and 2010 in 2005\$/tC. The estimates in this table were grown in accordance with the growth associated with the Nordhaus' 2005 and 2010 estimates*

c. *Public Utilities Commission of the State of California, 2007. Energy Division Resolution I.D. # 6931, Resolution E – 4118, October 4, 2007, http://www.cpuc.ca.gov/PUBLISHED/COMMENT_RESOLUTION/73147.htm.*

d. *Idaho Power Company, 2004. Technical Appendix for the 2004 Integrated Resource Plan, July 2004, http://www.idahopower.com/energycenter/irp/2004/2004IRPFinal.htm. Estimates grown assuming a 5 percent interest rate, which is the growth rate for the California Public Utilities Commission's value from 2004-2023.*

e. *United States Environmental Protection Agency's Analysis of Senate Bill S.280 in the 110th Congress, The Climate Stewardship and Innovation Act of 2007, http://www.epa.gov/climatechange/economicanalyses.html.*

f. *Murray, B. and M. Ross, 2007. The Lieberman-Warner America's Climate Security Act: A Preliminary Assessment of Potential Economic Impacts Lieberman-Warner, NI PB 07-04, Nicholas Institute for Environmental Policy Solutions, Duke University, October, http://www.nicholas.duke.edu/institute/econsummary.pdf.*

g. *U.S. EPA (2009).*

h. *Climate Market Daily, Volume 3 Issue 224, November 15, 2007.*

i. *Deutsche Bank, 2007. "Banking on Higher Prices: We See EUAs at E35/t Over 2008-20", Global Markets Research, July 23, 2007.*

j. *The range reflects the range of results from the three models reported on in Clarke et al. (2007). The corresponding CO_2 concentration level for 3.4 W/m^2 is 450 ppm, which is approximately a 550 ppm CO_2 equivalent concentration level.*

Unfortunately, comparing what is left—non-optimal SCCs and marginal mitigation costs—is also problematic (e.g., Holladay and Schwartz, 2009).

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[50] All values in table 5 were adjusted to 2006\$/tCO_2. Some sources provided explicit values or growth rates for future years. Others were grown for future years using the estimates given or growth rates from similar types of estimates. See table notes for details.

Current non-optimal marginal benefit and marginal mitigation cost estimates have for the most part been generated independently by impact or mitigation studies respectively. As a result, they are derived from different frameworks with different assumptions and scenarios for population, income, technology, emissions, climate change, and the carbon cycle. In addition, most SCC estimates represent the value of the first unit of emissions reduction in a particular year off of a baseline, while marginal cost values for mitigation represent the value of the last unit of reduction (presumably in the same year) off of a different socioeconomic and biophysical condition. Another issue is the failure to account for *net* changes in global emissions when using SCC estimates. SCC estimates—global and domestic—are only valid for a unit change in global emissions. Emissions estimates associated with domestic policies are frequently not estimates of global emissions changes. The SCC can only legitimately be applied to net global emissions changes. Finally, some try to make marginal comparisons in a specific year. These are not particularly meaningful because the annual growth rates for marginal benefit and costs are not the same, with the former growing as a function of atmospheric concentration, socioeconomic condition, and proximity to thresholds, while the later rises at the average risk free rate of interest for private investment.[51] Overall, these methodological and conceptual inconsistencies invalidate comparison. Not to mention the additional complication of uncertainties and omissions in SCC estimates, as well as uncertainty in marginal cost estimates.

Internally consistent models that endogenously model both benefits and costs can overcome these issues (e.g., Nordhaus, 2008; Tol, 2009); however, they are still confronted with and confounded by an even more basic issue—uncertainty.

Uncertainty about impacts is certainly the largest single factor complicating decisions. The uncertainties make it difficult to use impacts information to define economically efficient standards or an emissions pathway. Instead of a specific deterministic (or expected) point or pathway of points where the marginal benefits of emissions changes equal the marginal costs, we are confronted with a range of benefit (as well as cost) possibilities as analysts and decision-makers must prudently consider a spectrum of potential long-run assumptions. As a result, economically optimal standards cannot be specified, and even benefit-cost ratios are less reliable. Likewise, socially optimal price paths, while conceptually attractive, cannot be identified with confidence given quantified and unquantified uncertainties.

Uncertainty analysis, which considers expected values, changes in the distribution of different outcomes, and attitudes towards risk, is conceptually and practically preferable. However, with the characteristics of distributions uncertain, and important unquantified risks, it is unlikely to ever be able to boil information down to a single number or path that is robust and defensible enough for setting economically optimal standards or an emissions

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[51] If inconsistencies were addressed, a better comparison would be to compare the net present value of total benefits and total costs.

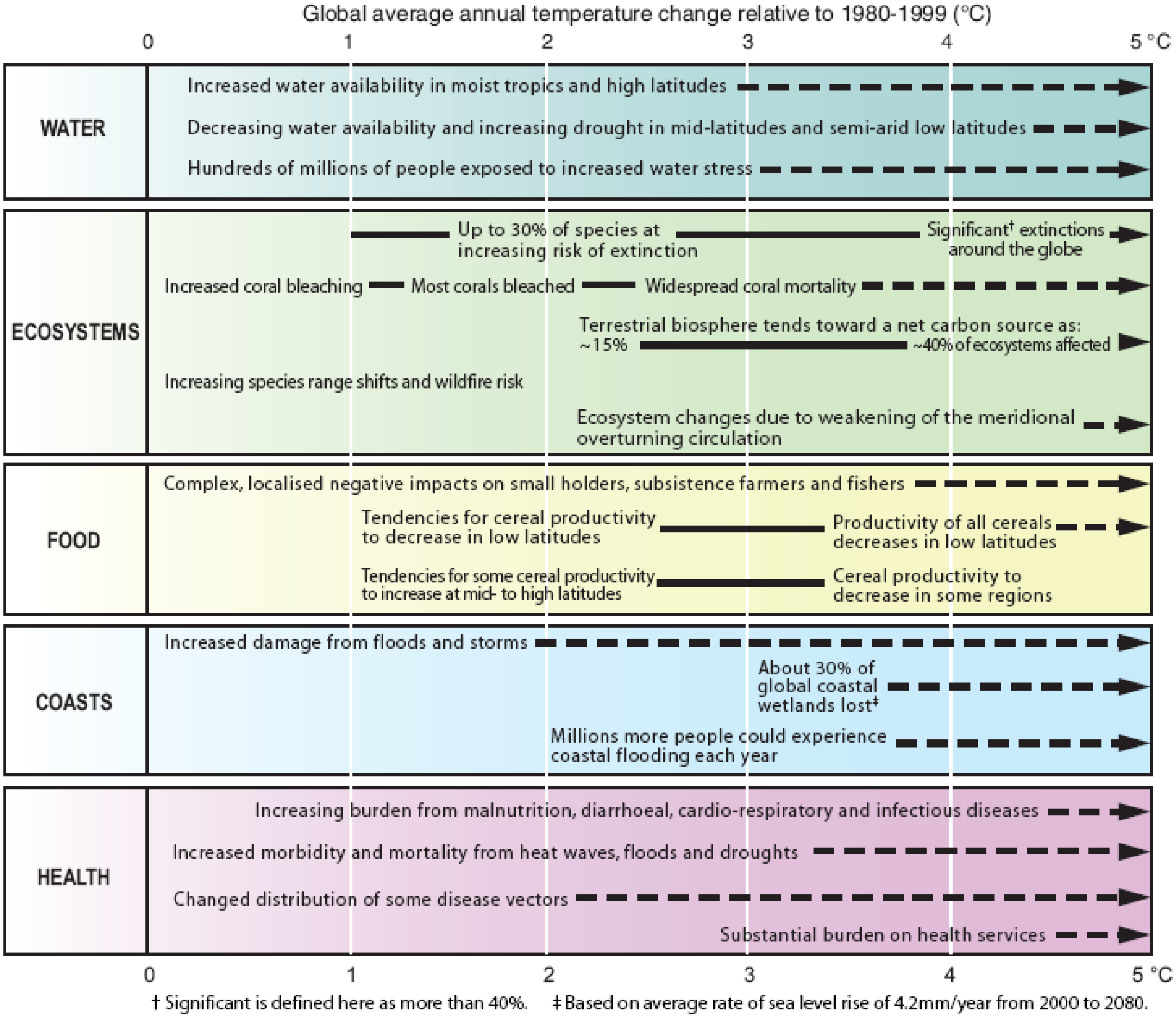
pathway. Nonetheless, optimal pathway analysis can still be instructive in that it can provide benchmarks for sensitivity analysis that explores the quantified and unquantified uncertainty space.

Quantifying non-incremental changes*.* Policies with non-incremental effects—on emissions and/or economic and biophysical systems, require frameworks able to capture interactions and feedbacks in and between economic and biophysical systems that are expected with higher levels of emissions reductions and large shifts in climate. Current SCC modeling frameworks do not capture these elements. Furthermore, the primary climate and impacts information currently available for estimating non-incremental benefits is, in and of itself, difficult for policy-makers to lean on.

Current information provides a fairly incomplete picture with respect to the implications on non-incremental changes in emissions, climate, and potential impacts. Overall, we cannot characterize distributions of most impacts, much less emissions and climate, especially thresholds and potential impacts outside of observed variability. Nor can we monetize many impacts. For instance, the IPCC's summary of current climate modeling characterizes only a part of the uncertainty. Figure 1 represents model uncertainty, i.e., the range of results across models. What is missing is parametric uncertainty, i.e., a distribution of results from a single model with varying parameter assumptions. If parametric uncertainty were also included, the uncertainty bands for each emissions pathway would be wider.

There are also complications to using the current impacts literature to estimate a total impact response to large climate changes. Net impacts of climate change are determined by more than climate change. Ecosystem and socioeconomic system conditions and responses are key determinants. Figure 3 from the IPCC WGII (2007) Summary for Policy Makers, is a nice visual cross-sector summary of potential impacts with increasing levels of global average temperature change. A different visual representation of the same information was generated by Smith et al. (2009). However, these figures should be viewed and used with caution for three reasons, especially for use as a sliding scale to estimate avoided impacts. First, the information was generated from disparate studies with different methodologies and applications, and fundamental differences in assumptions. As a result, it is difficult to construct a consistent comprehensive picture of change in impacts across sectors and regions. For instance, the water impacts for a 3 degrees Celsius increase are not necessarily correlated with those for food and health. Domestically, we face the same problem trying to, for example, construct a consistent picture of heat health impacts in Chicago, snow pack changes in the Sierra Nevada, precipitation effects on Midwest agriculture, sea level effects on Florida (gradual changes and storm surge, and potentially those associated with West Antarctic ice sheet collapse), and forest fire and pest changes in Canada that effect the carbon cycle and US timber markets.

Figure 3. Summary Impacts Information by Sector (*Source: IPCC WGII 2007)*

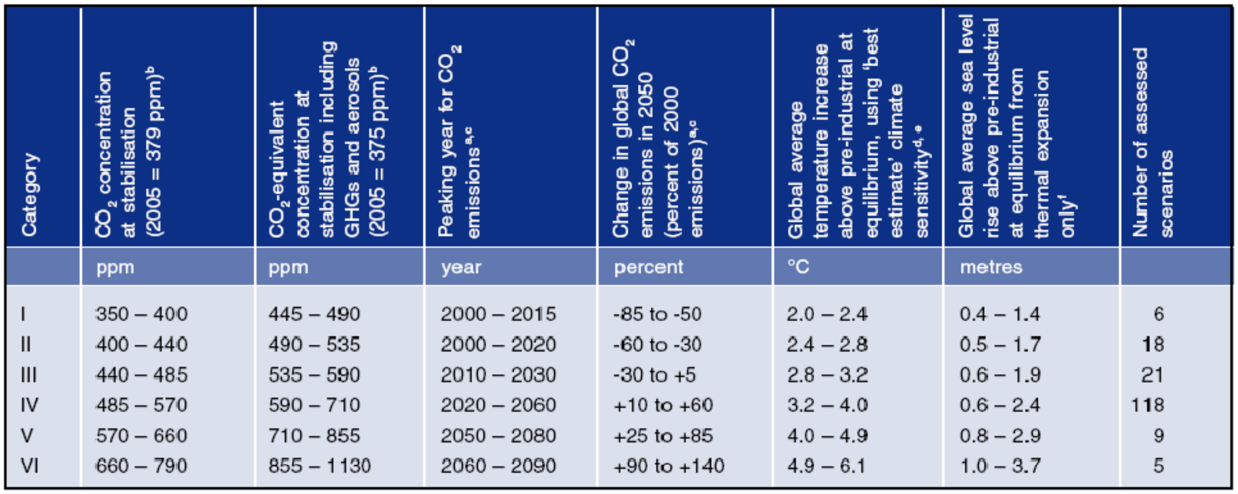


Second, an additional related complication in the current literature is that uncertainty at one impacts scale confounds the utility of information at another scale. For example, uncertainty in spatial downscaling diminishes the utility of grid-level impacts results.

Third, consideration of the interactions across impact categories (sectors) and global regions is minimal to non-existent. For example, how might vector borne illness incidence in different countries be affected by water scarcity, agricultural productivity and trade, and changes in migration patterns? Third, potential avoided impacts for decreases in projected temperature changes have not yet been explicitly modeled and estimated in the literature. Significantly adjusting the climate will require large scale socioeconomic transformation to produce the necessary mitigation (e.g., Clarke et al., 2007), and large anthropogenic emissions reductions will alter atmospheric composition and chemistry, and ocean and terrestrial ecosystems, and subsequently natural endowments from business as usual projections. In other words, the world will be a different socioeconomic and biophysical place under large-scale mitigation, with resulting changes in the exposure and vulnerability to climate change.

Unfortunately, our understanding of the transformation itself is fairly incomplete. While there have been significant advances (IPCC WGIII, 2007, Chapter 3), we only have a partial characterization here as well. Table 5 provides a summary of the recent climate stabilization scenarios literature, parsed into six stabilization level categories. While the ranges for the timing and level of emissions reductions are very useful for characterizing the relative demands of more stringent targets, the results, like the temperature change results in Figure 1, only capture model uncertainty, and only partially. For instance, a different trajectory will be cost-effective for a particular stabilization target under alternative plausible assumptions for future population and income growth, regional participation in abatement, non-climate policies, technology (availability, cost, and diffusion), or biophysical parameters and responses.

Table 5. Characteristics of Post-Third Assessment Report Stabilization Scenarios (*Source: IPCC WGIII 2007; IPCC SR 2007)*



Category	CO_2 concentration at stabilisation (2005 = 379 ppm)[b]	CO_2-equivalent concentration at stabilisation including GHGs and aerosols (2005 = 375 ppm)[b]	Peaking year for CO_2 emissions[a,c]	Change in global CO_2 emissions in 2050 (percent of 2000 emissions)[a,c]	Global average temperature increase above pre-industrial at equilibrium, using 'best estimate' climate sensitivity[d, e]	Global average sea level rise above pre-industrial at equilibrium from thermal expansion only[f]	Number of assessed scenarios
	ppm	ppm	year	percent	°C	metres	
I	350 – 400	445 – 490	2000 – 2015	-85 to -50	2.0 – 2.4	0.4 – 1.4	6
II	400 – 440	490 – 535	2000 – 2020	-60 to -30	2.4 – 2.8	0.5 – 1.7	18
III	440 – 485	535 – 590	2010 – 2030	-30 to +5	2.8 – 3.2	0.6 – 1.9	21
IV	485 – 570	590 – 710	2020 – 2060	+10 to +60	3.2 – 4.0	0.6 – 2.4	118
V	570 – 660	710 – 855	2050 – 2080	+25 to +85	4.0 – 4.9	0.8 – 2.9	9
VI	660 – 790	855 – 1130	2060 – 2090	+90 to +140	4.9 – 6.1	1.0 – 3.7	5

5. Conclusions – principles and components of an impacts assessment framework

This paper assessed the climate change impacts information needs of federal decisions through two steps. First, it evaluated a variety of recent decisions that considered impacts. Next, it described the biophysical and economic nature of GHGs and climate change. The paper then reviewed the state of impacts knowledge for policies with incremental versus non-incremental implications for GHG emissions and climate change. That section also highlighted challenges that confront decision-makers who need to work with the information available. A number of conclusions can be derived from these discussions that should be viewed as principles for impacts decision-making and basic components for an analytical framework. These are presented below. This section also identifies various research opportunities for improving impacts analysis capabilities, and ultimately our understanding.

Principles for incorporating impacts into federal decisions

There are certain decision-making and analytical realities associated with the scientific nature of climate change and the state of knowledge. These realities can be summarized as principles. First and foremost is the need to view policies with incremental and non-incremental emissions changes differently given current capabilities. Next is a set of common principles for utilizing impacts information in policies with either incremental or non-incremental emissions implications.

- *Treat incremental and non-incremental policies differently.* Given differences in biophysical and economic responses and feedbacks, different analytical approaches are appropriate for policies with small and large emissions and climate implications. Current capabilities are acceptable for policies with incremental emissions effects, but are not robust enough to guide climate (non-incremental) policy. New capabilities are needed for non-incremental policies.

- *Internalize global and intergenerational externalities.* Irrespective of the policy mechanism (market or command-and-control), addressing an environmental problem is a question of internalizing economic externalities. Domestic GHG emissions have global effects up to and beyond one hundred years. Therefore, federal decisions need to consider the global and intergenerational effects of changes in GHG emissions. For incremental policies, this implies using global marginal benefit/cost estimates like the SCC (social cost of carbon), while for non-incremental policies, structured modeling is needed to capture global and over century long biophysical and economic feedbacks and interactions.

- *Model the scope of GHGs.* Global and very long-run modeling is needed, which is a dramatic shift in paradigm from standard historical practice for other domestic environmental decisions such air quality. Even modeling of climate change impacts at a local scale requires consideration of alternative climates, which requires modeling or making assumptions about global economic responses, policy responses, and emissions changes. For instance, to estimate the benefits of U.S. based emissions reductions to the U.S., you need to estimate net changes in global emissions.

- *Contend with uncertainty beyond typical levels.* Given the global and temporal scope, decisions must contend with uncertainties larger than those associated with most other environmental decisions. As a result, ranges of impacts estimates are appropriate and prudent. Uncertainty analysis will also be valuable for ranking policies and for quantifying changes in risk (and valuing those changes) for risk management. However, given unquantifiable and difficult to quantify uncertainties, sensitivity analysis will continue to be important for assessing potential outcomes. In particular, scenarios are critical, as they allow for consideration of more difficult to quantify alternative biophysical and economic futures. For incremental policies, this implies consideration of ranges of marginal values as well as expected values, while for non-incremental policies, it implies broad sensitivity and uncertainty analysis in order to more fully consider potential risks associated with variability, thresholds, extreme weather, and catastrophic events and move beyond central or best guess assessment.

- *Characterize uncertainty and value risk.* Ultimately, managing climate change is a question of managing risk, and characterizations of risk are essential—both in terms of the likelihood and magnitude of outcomes and consideration of the value of changes in risk. While knowing precise impact distributions is unlikely, robust statements are possible about changes in distributions, such as shifting distributions right or left and making them more or less compact with larger shifts in the right tail. Also, evaluation of risk attitudes is important as they will affect the magnitude of the suggested response. Decision-making under uncertainty requires an explicit or implicit societal valuation of risk. For incremental analysis, a risk premium can be estimated and included in SCC estimates, while for non-incremental analyses, greater (lower) risk aversion will suggest a stronger (weaker) reaction in hedging against the risks.
- *Account for the extraordinarily long investment horizon.* Changes in GHG emissions are investments with returns well beyond the time horizon captured in current markets. Discount rates of 3 percent and lower are appropriate for the quantification of climate change impacts over the scientifically relevant timeframe. Discount rates in this range are consistent with the very long investment horizon and the corresponding uncertainty. It is also reasonable for discount rates to change over time with changes in economic growth and/or explicit consideration of uncertainty.
- *Use non-monetary impacts information.* Monetization of impacts is challenging given uncertainties and the fact that many impacts are non-market effects (e.g., environmental services, and existence and option values for species and ecosystems) and are not captured through market responses, as, for example, changes in heating and cooling demand would be. Quantitative estimates of biophysical impacts (e.g., changes in ecosystems) are therefore especially important, and can be readily used in a risk management approach to facilitate decisions about unacceptable risk. For incremental policies, this implies recognizing the deficiencies in current monetary marginal value estimates both in the development and use of estimates. For non-incremental policies, it implies consideration of both non-monetary and monetary quantified information for assessing risks, identifying acceptable risk thresholds, and evaluating opportunities for avoiding risk.
- *Use qualitative (proxy) impacts information.* Qualitative information can be meaningful and valuable to decisions and can complement and supplement monetized benefits estimates by providing a more expansive characterization of changes to climate risks.

For instance, projected changes in climate variables, such as average temperatures and sea level rise, can serve as meaningful proxies for changes in the risk of all potential impacts. This would include impacts that can be monetized, as well as those that have not been monetized but can be quantified in physical terms (e.g., water availability), and those that have not yet been quantified (e.g., forest disturbance) or are extremely difficult to quantify (e.g., catastrophic events such as collapse of large ice sheets and subsequent substantial sea level rise). Proxy impacts information can inform incremental and non-incremental decisions in a similar fashion to non-monetary information.

Components for an analytical framework

How can we provide better impacts information for decision-making? A framework is needed that recognizes the state of the literature and the substantial and persistent uncertainties associated with climate change. The framework should also be designed to support the multitude of policy questions. The information requirements for evaluating climate risks and developing response strategies and priorities are vast—with global and local, as well as near- and long-term, information needed for numerous and disparate categories. Similarly, decisions of every type and scale will affect GHG emissions and sequestration regardless of whether they are designed to influence climate or something else, such as air quality, energy independence, or forest health. This creates a need for consistent consideration of the implications on GHG emissions across decisions.

With these things in mind, we suggest the following basic components for an analytical framework for impacts:

For non-incremental emissions decisions

- *Structured modeling.* More structural, integrated assessment frameworks are needed than that currently used in SCC modeling. These frameworks need to capture biophysical and economic interactions and feedbacks across regions, sectors, and time. Such frameworks do not yet exist. A framework like this can also inform and be complemented by location and sector specific analyses.
- *Consistency.* Consideration of and consistency across all three dimensions—climate, ecosystem, and socioeconomic—is needed for robust assessment of impacts within and across sectors and regions. This was a central motivation for the approach for new integrated scenarios from the scientific community (Moss et al., 2008). Consistency is also needed to meaningfully estimate avoided impacts, i.e., the change in impacts between a reference and alternative future. This should be a priority research area. Consistency will substantially improve the quality and comparability of alternative

impacts futures and provide stronger ties to mitigation options, as well as facilitate joint mitigation-adaptation decision-making.[52]

- *Multiple models and scales.* It is unreasonable to think that a single model will ever be able to answer policy questions relevant to every spatial and temporal scale of concern with climate change. Multiple models are needed that provide insights about global, regional, and local effects—near- and long-term. Assembling a consistent and coherent picture of so many scales is a substantial task that will require common assumptions and significant development coordination. In a framework such as this, more aggregate models would be calibrated to finer resolution models, and the aggregate models would provide broader market, biophysical, and temporal context to the finer resolution models.
- *Risk management application.* Given uncertainties, an iterative risk management approach is practical. Policy-makers can define a level of "acceptable" risk, with respect to some metric—e.g., emissions reduction pathway, atmospheric concentration level, radiative forcing, temperature change, or specific set of impacts—with the expectation of learning from today's actions and in the future revising the course accordingly. Risk management can accommodate economic, non-economic (e.g., biophysical), and non-scientific (e.g., equity, political) inputs.[53]
- *Strategic analysis application.* The net benefits of domestic mitigation and adaption will depend on the actions of other countries. Strategic analysis of international responses to domestic policies and proposals is prudent not only for internationally negotiated actions, but for domestic decisions which can be a signal to other countries and thereby affect domestic direct and indirect benefits, i.e., those respectively felt directly in US jurisdictions and indirectly through economic and biophysical feedbacks and US public and private value for international interests.

For incremental emissions decisions

- *Global values.* It is appropriate to use ranges of global marginal values in addition to expected values in determining or assessing the implications of policies with incremental effects on global GHG emissions. Global present value estimates should be used in order to internalize the externalities and guide incremental policies towards an efficient effect on the climate public good.[54]

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[52] Consistency will help inform how we decide on the portfolio of adaptation and mitigation strategies for near-term impacts that are inevitable and long-term impacts that could be avoided through mitigation.

[53] In parallel, it would be valuable to estimate societal risk tolerance (i.e., the curvature of the utility function) for use in assessing risky outcomes. See the paper by Yohe in this volume for a detailed discussion of iterative risk management.

[54] Both the United Kingdom and the European Commission are following the economic principles in their use of the global social cost of carbon (SCC) for valuing the benefits of GHG emission reductions in regulatory impact assessments and cost-benefit analyses (Watkiss et al, 2006). The United Kingdom is now using what they refer to as a shadow price of carbon (SPC) which is based off of climate stabilization trajectory (UK Defra, 2007). However,

- *Reference projection.* For now, the values could be conservatively computed off of baseline projections (i.e., absent potential future climate policies). Estimates off of baseline projections, versus aspirational climate policy pathways, are more consistent with current non-climate policy decisions that have marginal global GHG emissions implications. Baseline SCCs would also be consistent with climate change policy proposals since baseline SCCs more efficiently internalize the climate change risks that the government wishes to avoid or hedge against with the proposed climate policy. If global emissions, socioeconomic, and biophysical trajectories are significantly modified by future climate policy, the estimates of marginal values can be revised. Specifically, a trajectory of revised marginal values can be computed for the corresponding global emissions pathway.
- *Uncertainties and deficiencies.* These need to be considered in using marginal value estimates. They can be dealt with by considering alternative values, including high end values that can be reasonably considered given the expected negative bias in current estimates and risk management motives.
- *Future improvements.* Over time, estimates can be improved with updated information and additional impacts as new detailed sector and region specific research emerges. Methodologically, expected value estimates should be developed that account for uncertainty and risk preferences, and that consider thresholds and variability. Estimates over time and for non-CO_2 GHGs are also needed.

In addition to the development priorities already mentioned, new research is needed to more fully characterize the uncertainty space for climate responses and potential impacts and to identify which uncertainties can and cannot be quantified. Recall that current climate and stabilization modeling has primarily captured model uncertainty. It is important to also recognize that the key uncertainties will vary by policy question and the analytical platform. There are different uncertainties at different scales and for different tools, where uncertainties at one scale can confound the utility of information at another scale. Identifying these is critical to producing meaningful information.

Federal decision-makers will continue to need to make decisions that have intentional or unintentional consequences for future climate change risks. The nature of the public good and the state of knowledge will force these decisions to be made under substantial uncertainty, and the issues associated with this reality will have to be continually confronted.

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conceptually, an SPC would undervalue the impact of today's policies with incremental global emissions effects that are marginal to the current non-stabilization trajectory.

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WORKSHOP PROCEEDINGS

Assessing the Benefits of Avoided Climate Change: Cost-Benefit Analysis and Beyond

The Need for a Fresh Approach to Climate Change Economics

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Economics for Equity and the Environment Network

Abstract

The integrated assessment models (IAMs) that economists use to analyze the expected costs and benefits of climate policies frequently suggest that the "optimal" policy is to do relatively little in the near term to reduce greenhouse gas emissions. This conclusion seemingly conflicts with the emerging scientific consensus about the irreversibility of climate change and the risks of catastrophic impacts. We trace this disconnect to contestable assumptions and limitations of IAMs when applied to climate change. For example, they typically discount future impacts from climate change at relatively high rates that are empirically and philosophically controversial when applied to intergenerational environmental issues. IAMs also monetize the benefits of climate mitigation on the basis of incomplete and sometimes speculative information about the worth of human lives and ecosystems and fail to account for the full range of scientific uncertainty about the extent of expected damages. IAMs may also exaggerate mitigation costs by inadequately capturing the socially determined, path-dependent nature of technological change and ignoring the potential savings from reduced energy utilization and other opportunities for innovation.

A better approach to climate policy, drawing on recent research on the economics of uncertainty, would avoid the limitations of the narrow cost-benefit comparisons of IAMs and reframe the cost of mitigation as buying insurance against irreversible and catastrophic events, the avoidance of which would yield large but unquantifiable benefits. Policy decisions should be based on a judgment concerning the maximum tolerable increase in temperature and/or atmospheric carbon dioxide concentrations given the state of scientific understanding. In this framework, the appropriate role for economists would be to determine the least-cost strategy to achieve that target.

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[1] A more technical version of this paper titled "Limitations of Integrated Assessment Models of Climate Change" is forthcoming in *Climatic Change*.

[2] The listing of authors is alphabetical and does not imply precedence.

1. Introduction

The scientific consensus on climate change is clear and unambiguous; climate change is an observable phenomenon with the potential for catastrophic impacts (Intergovernmental Panel on Climate Change, 2007a). The large-scale computer models that helped build the scientific consensus on climate change and its impacts have acquired a good reputation in the scientific community. The leading general circulation models (GCMs) demonstrate ever more detailed and extensive descriptions of the physical processes of climate change, which are testable either directly or indirectly through comparison with historical climate data. These models are grounded in physical laws that are well-established both theoretically and empirically.

Economists also employ multi-equation computer models in their approach to climate change. These models, known as integrated assessment models (IAMs), build on the results of GCMs to assess the economic benefits and costs of climate policy options. Economists use "policy optimizing" IAMs to identify the "best" policy response, the option that maximizes the difference between benefits and costs (i.e. net benefits).[3] As the debate over climate policy shifts from scientific uncertainty to balancing costs and benefits, the results of IAMs grow in importance. Economists since the 1990s have largely been supportive of action to mitigate climate change; the main disagreement today is whether to act aggressively to minimize the risks of climate impacts, or to make a slow transition to minimize the economic impacts of policies to mitigate climate change. Interpreting IAMs properly is critical for decision makers as they weigh the appropriate response to the climate problem.

While many scientists advocate more stringent emissions targets aimed at stabilizing atmospheric greenhouse gas (GHG) concentrations during this century, the results of IAMs often suggest a cautious approach that involves only modest early action to limit greenhouse gas emissions with the limits becoming more stringent slowly over time (e.g., Kelly and Kolstad, 1999; Tol, 2002a; Manne, 2004; Mendelsohn, 2004; Nordhaus, 2007a). For example, the optimal emissions reduction rate according to economist William Nordhaus' most recent version of the widely cited DICE model is only 14 percent compared to a "business-as-usual" or no-control emission scenario in 2015, rising to 25 percent by 2050 and 43 percent by 2100 (Nordhaus, 2007a).

In contrast, the European Union has called for the global community to reduce carbon emissions to 50 percent below 1990 levels by 2050, with emissions declining to near zero by the end of the century. This goal is based on a scientific assessment that the risk of climate catastrophe increases dramatically as greenhouse warming exceeds roughly 2 °C above the preindustrial global average temperature. Under Nordhaus' "optimal" policy, the

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[3] Mastrandrea (2009) distinguishes between "policy optimizing" and "policy evaluating" integrated assessment models. Our paper is primarily concerned with "policy optimizing" models that are used for formal cost-benefit analysis of climate mitigation policies (e.g., the DICE model).

warming exceeds 3 °C, thus incurring much greater future risk compared to the EU target. Other IAMs have estimated significant welfare losses in the United States from the recent suite of Congressional proposals to limit carbon emissions to 50-80 percent below 1990 levels by 2050 (Paltsev et al., 2007). Still other IAMs have even estimated a positive net benefit from climate change in OECD countries, while acknowledging net losses in poor countries. This has led leading researchers like Tol to conclude that "climate change and greenhouse gas abatement policy is essentially a problem of justice" (Tol, 2002b).

How can we reconcile the apparent disconnect between the science, which provides an objective characterization of the potentially catastrophic implications of climate change, and the results of IAMs indicating that aggressively mitigating climate change is too costly? Unlike physics-driven climate models, economic models mix descriptive analysis and value judgments in ways that deserve close and critical scrutiny. To build their models, economists make assumptions that reflect long-standing practices within economics but that nonetheless are associated with well-known conceptual and empirical problems. Alternative models, built on different subjective assumptions that are just as plausible as those embedded in commonly cited IAMs, lead to qualitatively different results, illustrating the underlying limitations of cost-benefit analysis as applied to climate change (e.g., Cline, 1992; Stern, 2006; Ackerman and Finlayson, 2006).

Scientific understanding of the risks of climate change is continuously improving. For example, the review article by Hall and Behl (2006) highlights the inability of policy-optimizing IAMs to incorporate the consequences of climate instability and rapid large-scale shifts in global climate. Lenton et al. (2008) identify and catalogue potential "tipping elements" in the climate system that could lead to large scale shifts. To account for these and related analytical shortcomings, a variety of decision-making frameworks extending beyond conventional cost-benefit analysis have been identified (Toth et al., 2001). These include "tolerable windows" and "safe landing" approaches, "robust decision-making," and "cost-effectiveness analysis," among others. A recent conference was devoted to the implications of "avoiding dangerous anthropogenic interference with the climate system" as a guide to policy-making (Schellnhuber et al., 2006). Our objective in this article is not to provide either a comprehensive review of the most recent developments in climate science,[4] or an all-encompassing treatment of decision-making with regard to climate. Rather, our critique focuses on the conceptual economic framework of the most common utility-maximizing IAMs and on some of the most important shortcomings in how these models represent climate protection costs and benefits. The focus of this paper is conceptual.[5]

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[4] Examples of articles dealing with the kinds of issues treated by Hall and Behl (2006) include Kennedy et al. (2008), Hoegh-Guldberg et al. (2007), and Buffett and Archer (2004).

[5] See the paper in this volume by Mastrandrea for information on how policy-optimizing IAMs go about estimating climate damages or the benefits of avoided climate change.

We identify three principal areas in which the standard economic approach as applied to climate change is arguably deficient: the discounted utility framework, which attaches less weight to the impacts of climate change on future generations; the characterization and monetization of the benefits of mitigation; and the projection of mitigation costs, which rests on assumptions about the pace and nature of technological change. We address these issues in the following three sections and conclude with recommendations for an alternative approach to the economics of climate change that reflects recent advances in the economics of uncertainty.

2. The Discounted Utility Framework and its Implementation through IAMs

The economic theory from which IAMs are derived starts from a particular understanding of human nature and preferences and seeks to identify the choices that will maximize the satisfaction of those desires. Echoing nineteenth century utilitarian moral philosophy, economists refer to satisfaction as "utility" and assume it to be quantifiable in economic terms—in short, an ideal objective for maximization. Climate outcomes enter the analysis as factors that increase or decrease human satisfaction. IAMs estimate the climate policy scenarios that maximize social utility.

The "optimal" target these models identify is not a pre-determined climate condition judged to be conducive to human well-being, but rather the maximum subjective satisfaction based on projected but uncertain economic benefits and costs that the models presume to be foreseeable. It is here that the disconnect between the science and the economics of climate change begins. Maximization of satisfaction under these assumptions does not necessarily yield a climate target close to what scientists consider necessary to avoid the most serious risks of climate change. If IAMs mischaracterize the benefits of avoided climate impacts or fail to appropriately model scientific uncertainty about future damages, the results will not account for the most serious risks that scientists identify, yet these risks are the most important ones to reduce. Moreover, in order to compare utilities across generations, economic models invoke assumptions about how much additional weight present outcomes deserve over future outcomes. A value judgment about the rate at which society is willing to trade present for future benefits is embedded in the model's discount rate. But when economic models discount future well-being, the present value of the harms caused by future climate change can easily shrink to the point where it is hardly "worth" doing anything today in order to prevent climate change.

The basic construct of the typical utility-maximizing IAM involves a social welfare function that stretches into the distant future (far enough ahead to experience significant climate change). In simplest terms, the social welfare function maximizes the sum total utility (or welfare) of individuals over time. Frequently, IAMs assume a single representative agent in each generation, or equivalently, that all members of a generation are identical in both consumption and preferences. With slight variations between models, the generic framework is to maximize

$$W = \int_0^\infty e^{-\rho t} U[c(t)]dt \qquad [1]$$

where W is social welfare, ρ is the "rate of pure time preference," $c(t)$ is consumption at time t, and $U[\bullet]$ is the utility function specifying how much utility is derived from a particular level of consumption.

Equation [1] and the techniques required to maximize W embody a number of questionable assumptions. First, note the significance of a positive rate of pure time preference in the model. The rate of time preference reflects society's attitudes towards present verses future utility. The term $e^{-\rho t}$ expresses how society weights utilities at different times. If the parameter ρ is positive, society values the utility of people living today more than the utility of people living in the future. This implies that the well-being of this generation matters more than that of its children, who in turn matter more than their children, and so on. If a generation is 35 years in duration and $\rho = 0.05$ the weight given to a unit of utility at the end of the second generation is only 3 percent of the weight given to the same unit of utility today. If ρ is sufficiently high, the future benefits of avoided climate change essentially disappear from the analysis, even if the damages are grave.

As is standard practice in economics, most IAM analyses assume that ρ is positive. Is it appropriate to discount the welfare of future generations, and if so, at what rate? Economists have long struggled with this question. The classic article on this subject was published in 1928 by Frank Ramsey. Ramsey himself understood that ρ reflected an ethical weighing of the well-being of different generations and argued on philosophical grounds for a zero rate of pure time preference:

> [I]t is assumed that we do not discount later enjoyments in comparison with earlier ones, a practice which is ethically indefensible and arises merely from the weakness of the imagination; we shall, however, …include such a rate of discount in some of our investigations (Ramsey, 1928, p. 543).

Numerous economists and philosophers since Ramsey have argued that weighing all generations equally by setting ρ equal to zero is the only ethically defensible practice (for modern treatments, see Cline (1992) and Broome (1994)); yet IAMs continue to assume $\rho > 0$.[6]

Second, implicit in the formulation of a social welfare function is the aggregation of preferences across different individuals. In equation [1], this aggregation depends only on the total consumption of goods and not on the distribution of that consumption. Whatever

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[6] This is at least in part a mathematical necessity: with $\rho = 0$, the integral in equation [1] does not converge if future utility is constant or growing (or merely declining sufficiently gradually) (Dasgupta and Heal, 1979).

method for aggregation is used, it necessarily involves value-laden assumptions.[7] This is an inescapable consequence of the discounted utility approach. Because the framework requires that preferences be compared and added within and across generations, it forces economists to make normative decisions regarding the comparison of individual utilities and discount rates. Though a social welfare function can be solved mathematically to yield the "optimal" solution, the solution is dependent on the values and biases that are unavoidably embedded in the model. If these assumptions are not stated explicitly—and often they are not—decision makers may take policy actions, unaware of some important social implications.

Third, it is worth noting that the discounted utility characterization of behavior for *individuals* that underlies this formulation of the social policy problem is not well supported by the evidence (Frederick et al., 2002). The optimizing psychological and behavioral assumptions adopted by economic modelers do not have the status of laws of nature. They are matters of convenience and convention, not deep structural features of human action (Laitner et al., 2000; Kahneman and Tversky, 2000).

3. Predicting the unpredictable and pricing the priceless

IAMs analyze the costs and benefits of climate mitigation. Cost-benefit analysis assumes that costs and benefits can be expressed in monetary terms with a reasonable degree of confidence. At least in principle, the costs of environmental protection consist of well-defined monetary expenditures, although there are significant problems in the standard approach to projecting mitigation costs, as discussed at the end of this section. The benefits of environmental protection, however, are generally more difficult to quantify. In the case of climate change, economists confront a double problem: the benefits of mitigation are both unpredictable and unpriceable.

The unpredictability of climate outcomes reflects in part what we do not know, because climate change is likely to cause non-marginal displacements that put us outside the realm of historical human experience. Unpredictability is reflected in what we *do* know as well. We know that the Earth's climate is a strongly nonlinear system that may be characterized by threshold effects and chaotic dynamics.[8] Under such conditions, forecasts are necessarily indeterminate; within a broad range of possible outcomes, almost anything

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[7] One implication of the aggregation method is that if all members of society have equal weight in the social welfare function and all experience diminishing marginal utility to the same degree, the social welfare at any point in time could be increased by redistribution of income from the wealthy to the poor, provided the effects of this redistribution on incentives to produce and save are ignored. An alternate approach—weighting individuals' contribution to social welfare function by their wealth—has obvious drawbacks from an ethical point of view. The same kinds of problems regarding aggregation across individuals and nations plague estimates of the costs of mitigating climate change – the distribution of the costs has a major impact on both the ethical evaluation of proposed policies and their political feasibility.

[8] See the paper in this volume by MacCracken for details about the physical science-based challenges for quantifying the benefits of climate policy.

may happen. IAMs, for the most part, do not account for this full range of uncertainty but instead adopt best guesses about likely outcomes, typically derived from the middle range of several estimates of climate impacts (Kelly and Kolstad, 1999; Tol, 2002a; Manne, 2004; Mendelsohn, 2004; Nordhaus, 2007a). The *Stern Review* (2006) represents an advance over standard practice in this respect, employing a formal technique (Monte Carlo analysis) to estimate the effects of uncertainty in many climate parameters. As a result, the *Stern Review* finds a substantially greater benefit from mitigation than if it had simply used "best guesses."

But underneath one layer of assumptions lies another. Even if we assume precision in predicting climate impacts, the problem of assigning meaningful monetary values to human life, health, and natural ecosystems still remains. This problem affects all cost-benefit analysis. Because a numerical answer is required, environmental economists have long been in the business of constructing surrogate prices for priceless values. Economic policy under the Clinton administration was to estimate the value of human life on the basis of the small wage differentials between more and less dangerous jobs. The Bush administration used responses to long questionnaires asking people how much they would pay to avoid small risks of death under abstract hypothetical scenarios.[9] Should the value of a human life depend on individual or national income levels? Should nature located in a rich country be worth more than if it is located in a poor country? These approaches are regularly applied in policy analyses to estimate monetary values for health and environmental benefits (Diamond and Hausman, 1994; Hanemann, 1994; Portney, 1994). Valuations of human life differentiated by national income were included in the IPCC's *Second Assessment Report* (1996), but were excluded from the *Third Assessment Report* (2001). Similar values, however, continue to appear in the economics literature, making their way into IAMs (Tol, 2002b; Bosello et al., 2006), where the lives of citizens of rich countries are often assumed to be worth much more than those of their poorer counterparts. IAMs that differentiate the value of human life by income would recognize greater benefits from mitigation if climate change were expected to claim more lives in rich countries than in poor countries. The highest mortality and morbidity rates from climate change, however, will be found in the developing world (IPCC 2004).

Income bias is inherent to the process of valuation. When asked how much they are willing to pay to protect some small part of the natural world (a technique called contingent valuation), the responses of people cannot help but reflect how much they are actually able to afford. This survey method may provide plausible information about subjective values for local amenities such as neighborhood parks. However, its appropriateness becomes questionable in a complex, interdependent world where essential ecosystem services are not always visible or local, and where incomes and information are unequally distributed. A consequence of contingent valuation is that IAMs are likely to find net benefits of near-term

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[9] See Ackerman and Heinzerling (2004), especially Chapter 4, pp. 75-81.

climate change because people living in colder northern climates are generally richer than those living in hotter southern climates. Even if benefits are thought to disappear after a few degrees, or a few decades, of warming, a high discount rate ensures that the early years of net benefits loom large in present value terms when compared to the more remote and heavily discounted later years of net damages.

For example, Nordhaus long maintained that there is a substantial subjective willingness to pay for warmer weather on the part of people in cold, rich countries. He observed that US households spend more on outdoor recreation in the summer than in the winter and, on the basis of that singular observation, concluded that subjective enjoyment of the climate in the United States would be maximized at a year-round average temperature of 20 °C (68 °F) (Nordhaus and Boyer, 2000). This is well above the current global average and is approximately the average annual temperature of Houston and New Orleans in the United States, or Tripoli in Libya. There are many people who live in areas hotter than Houston, but they are generally much poorer than the people who live in areas colder than Houston. Thus if willingness to pay is limited by ability to pay, contingent valuation would find a large net global willingness to pay for warming. In the 2000 version of DICE, this factor outweighed all damages and implied net benefits from warming until the middle of this century (Nordhaus and Boyer, 2000). However, that idiosyncrasy of the earlier DICE has been criticized (Ackerman and Finlayson, 2006) and the latest DICE (2007) no longer allows net benefits from warming (Nordhaus, 2007b).

A more quantifiable but equally contestable benefit from warming is its impact on agriculture. Early studies of climate impacts suggested substantial agricultural gains from warming, as a result of longer growing seasons in high latitudes and the effects of CO_2 fertilization on many crops. Mendelsohn et al. (2000) and Tol (2002a) incorporated large estimated agricultural gains from early stages of warming. Successive studies, however, have steadily reduced the estimated benefits as the underlying science has developed. Outdoor experiments have shown smaller benefits from CO_2 fertilization than earlier experiments conducted in greenhouses (IPCC, 2007b). Recent research predicts that the negative effects of ground-level ozone, which is produced by the same fossil fuel combustion processes that emit CO_2, may offset the impacts of a longer growing season and CO_2 fertilization and lead to a small net decrease in agricultural productivity in the United States (Reilly et al., 2007). Another recent study finds that the market value of non-irrigated farmland is highly correlated with climate variables (Schlenker et al., 2006). The optimum value occurs at roughly the current average temperature with slightly more than the current average rainfall. In this study, projections of climate change to the end of the century result in substantial losses in farm value, due primarily to crop damage from the increase in the number of days above 34 °C (93 °F). The earlier analyses also ignored the effects of extreme weather events, and crop pests and diseases that are now thought to be likely to increase in many places (IPCC, 2007b).

As these examples of potential benefits suggest, there is a significant degree of judgment—which may be purely subjective or scientifically outdated—involved in estimating the value of climate damages. It is not surprising then that IAMs are completely dependent on the shape of their assumed damage functions. It is conventional to assume that damages increase non-linearly as a quadratic function of temperature, based on the common notion that damages should rise faster than temperature. The *Stern Review* (2006) made the exponent on the damage function a Monte Carlo parameter, ranging from 1 to 3 (i.e., damages ranged from a linear to a cubic function of temperature). Even though Stern's modal estimate was only 1.3, the cases with a higher exponent had a large effect on the outcome. In later sensitivity analyses in response to critics, the *Stern Review* researchers showed that if the assumed damages were a cubic function of temperature, the result was an enormous increase in the estimate of climate damages, changing their prediction by more than 20 percent of world output (Dietz et al., 2007). Given that analysts do not know which exponent is correct, the ability of IAMs to estimate damages is severely limited by current understanding of how future impacts will develop. In short, unlike the physics-based modeling involved in GCMs, the results of IAMs are tied to arbitrary judgments about the shape of the damage function as we move into temperature regimes that are unknown in human or recent planetary history.[10]

In estimating the costs of mitigating climate change, IAMs rest again on problematic assumptions. We have good reason to believe that most IAMs overestimate the costs of achieving particular stabilization targets. Most IAMs exclude the possibility for "no-regrets" options—investments that could reduce emissions without imposing significant opportunity costs. These options do exist, largely in the area of improved energy efficiency (IPCC, 1996; Interlaboratory Working Group, 2000; Lovins, 2005; Elliott et al., 2006; Shipley and Elliott, 2006; Laitner et al., 2006; McKinsey Global Institute, 2007).

While estimating mitigation costs in dollar terms should be more straightforward in principle than estimating mitigation benefits, the evolution of new technologies needed for reducing future climate change is uncertain, particularly over the long time periods involved in climate modeling. Forecasts of mitigation costs, therefore, depend on assumptions about the pace of development of new (and existing) technologies and their costs. Many IAMs assume a predictable annual rate of productivity improvement in energy use, and/or a predictable rate of decrease in emissions per unit of output. Thus a paradoxical result emerges from the models' overly mechanistic structure. Because climate change is a long term crisis, and predictable, inexorable technological change will make it easier and cheaper to reduce emissions in the future; it seems better to wait before addressing the problem of climate change. Hence, most IAMs advocate a cautious approach that involves only modest early action to limit emissions with gradually increasing limits over time, but this conclusion rests on untested assumptions about future technologies.

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[10] The paper in this volume by Mastrandrea discusses IAM damage functions in more detail.

Models that assume endogenous technological change, wherein technological development responds to policy or economic signals within the model, reach different conclusions and frequently recommend more aggressive carbon abatement policies, with results varying according to how the models are (e.g., Goulder and Schneider, 1999; Gerlagh, 2007; for recent surveys of this literature, see the special issue of *Resource and Energy Economics* edited by Carraro et al., 2003; Edenhofer et al., 2006, and the special issue of *The Energy Journal* (IAEE 2006) in which it appears; and Gillingham et al., 2007). In contrast, IAMs that adopt more conservative assumptions about the pace of technological change typically estimate higher mitigation costs because they abstract away from the potential for learning-by-doing and the positive role public policy can play in steering investment choices and promoting technological change. But even models that include endogenous technological change are not empirically based. We still do not really know how big the spillover effects will be, or how significantly research and development will respond to a price signal. In general, however, economic models have tended to underestimate the pace of technological change and to overestimate the cost of solutions to environmental problems (Ackerman et al. 2009).

Ultimately, well-designed climate policy will play a decisive role in determining the pace and direction of technological change, how the costs of mitigation will be distributed, and what the overall "drag" on the economy will be from higher fossil fuel prices. Assumptions about how climate policy is formulated are key determinants of IAM results.

4. Discounting and Uncertainty

Even if IAMS could quantify the avoided damages of climate change and the costs of emissions mitigation, their results would still hinge on the fundamental philosophical and empirical problems inherent to discounting future consumption. By analogy with short-term financial calculations, it is typically asserted that future incomes and consumption should be discounted at the interest rate r (in contrast to utility, which is discounted at the rate ρ). In this case, we can think of r as the rate of return on risk-free assets. In the absence of uncertainty, the market rate of interest that emerges in a model based on the maximization of the W of equation [1] is given by the "Ramsey rule" used in many IAMs:[11]

$$r = \rho + \eta g \qquad [2]$$

where ρ is the rate of pure time preference, g is the rate of growth of consumption, and the parameter η describes how rapidly the marginal utility of consumption decreases as consumption increases.[12] The larger the growth rate of consumption, the wealthier future

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[11] To arrive at the simple form of equation [2], it is typically assumed that the utility function has the form of the "constant relative risk aversion" type, that is, $u(c)=(c^{1-\eta}-1)/(1-\eta)$. Ordinarily it is assumed that η is positive and has a value of 2 or greater.

[12] In other words, η embodies the "diminishing marginal value of income," the notion that the value of each additional dollar of income decreases as an individual gets richer.

generations will be, and the higher the market rate of interest will have to be to induce savings instead of current consumption. If future consumption is expected to be low, the market rate of return on savings does not have to be high to induce savings. Similarly, with a high rate of pure time preference, a higher rate of return on savings is necessary to compensate for forgone consumption in the present.

With r greater than zero, distant-future outcomes take on reduced importance in economic calculations. But this shrinkage of future values is not an inevitable consequence of equation [2]. If environmental damage is sufficiently great so as to reduce consumption in the future, then g may be negative and the discount rate will actually be *less* than the pure rate of time preference (Tol, 1994; Amano, 1997; Dasgupta et al., 1999). A sufficiently negative g could even make r negative in this situation.

The Ramsey rule of equation [2] does not represent the last word about discounting, however. First, equation [2] needs modification if the economy consists of multiple goods with different growth rates of consumption. If we define the economy to include environmental services, the proper discount rate for evaluating investments in environmental protection will be considerably lower than r, and possibly even negative. The rate of return on investments in environmental protection will be low as long as society views environmental services as weak substitutes for produced goods, and the growth rate of produced goods is greater than that of the environmental services sector, which may be constant or even declining (Hoel and Sterner, 2007).

Second, and more important, when uncertainty enters the picture, equation [2] is no longer valid. In the real world, we do not observe "the" market rate of interest, but rather a multitude of *different* rates of return to assets having different characteristics. The main thing that distinguishes assets from each other and accounts for their differing rates of return is that they do not carry the same degree of *risk*.

The importance for climate policy of the simple empirical fact that different interest rates are observed in the marketplace was pointed out by Howarth (2003).[13] Ignoring uncertainty about the consequences of climate change is a serious omission that is inconsistent with the evidence (Committee on Analysis of Global Change Assessments, 2007). In particular, the discount rate (or expected return) attached to a particular investment has to take into account the *covariance* (or statistical interdependence) between the asset's return and overall consumption.[14] Cochrane (2005, pp 13–14) puts it this way:

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[13] A number of other economists have begun to explore the consequences of uncertainty for discounting (e.g., Newell and Pizer, 2003; Ludwig et al., 2005; Howarth, 2009; Howarth and Norgaard, 2007; Sandsmark and Vennemo, 2007; Pesaran et al., 2007).

[14] The theory here is generic and at the heart of modern finance. Standard expositions can be found in Cochrane (2005), Mehra (2003) and Howarth (2003, 2009). The relationship between the expected return on an asset and its covariance with consumption is *[this footnote continued on next page]*

> *Investors do not like uncertainty about consumption. If you buy an asset whose payoff covaries positively with consumption, one that pays off well when you are already feeling wealthy, and pays off badly when you are already feeling poor, that asset will make your consumption stream more volatile. You will require a low price to induce you to buy such an asset. If you buy an asset whose payoff covaries negatively with consumption, it helps to smooth consumption and so is more valuable than its expected payoff might indicate. Insurance is an extreme example. Insurance pays off exactly when wealth and consumption would otherwise be low—you get a check when your house burns down. For this reason, you are happy to hold insurance, even though you expect to lose money—even though the price of insurance is greater than its expected payoff discounted at the risk-free rate.*[15]

This observation implies that even if the expected rate of growth of consumption is positive on average, considerations of precautionary savings and insurance can lower the discount rate appropriate for valuing climate protection investments (Howarth, 2007). The discount rate under uncertainty is quite different from the Ramsey rule discount rate given by equation [2].

Uncertainty about the underlying structure of the interaction between climate change and the economy creates additional problems for the discounted utility framework. In a series of pathbreaking papers, Weitzman (2007a, 2007b, 2009) has shown that climate catastrophes with low but unknown probabilities and very high damages dominate discounting considerations in formulating a policy aimed at reducing these risks. This uncertainty lowers the discount rate significantly because the possibility of very high damages implies that future consumption may decrease.

Finally, it should be noted that there are serious empirical problems with all of the discounting formulas. Even if plausible and/or historical values of the parameters underlying the calculations of discount rates (the coefficient of relative risk aversion, the growth rate and variance of consumption, the covariance between returns and the marginal utility of consumption, and the subjective rate of time preference) are used, these formulas do *not* yield discount rates that match those actually observed in the market. These anomalies between model assumptions and observed market rates go by names such

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$$E[r^i] \quad = \quad r^f - \frac{\operatorname{cov}[u'(c_{t+1}), r^i_{t+1}]}{E[u'(c_{t+1})]}$$

where $E[r^i]$ is the expected market discount rate for asset of type or risk class i and r^f is the risk-free discount rate. Equation [6] requires some interpretation, because $E[r^i]$ moves in the opposite direction as the price of asset *i,* and the marginal utility of consumption u' decreases as consumption increases.

[15] Or, consider the case of equities. Equities have high returns when consumption is high, so the covariance between the equity discount rate and the marginal utility of consumption is negative (because the marginal utility of consumption is lower when consumption is high). Hence the equity discount rate is higher than the risk-free rate because of the negative sign on the covariance term in the equation of footnote 8.

as “the equity premium puzzle” and “the risk-free rate puzzle,” and they show up strongly not only in data for the United States, but also in data for other countries with well-developed asset markets (Campbell, 2003; Mehra and Prescott, 2003). Despite an enormous amount of effort by the best economists to resolve these paradoxes (literally hundreds of scholarly papers have been published on these puzzles), there is no professional consensus on how the theory might be reconciled with observations. As Mehra and Prescott (who originally discovered the equity premium puzzle (1985)) comment,

> *The [equity premium] puzzle cannot be dismissed lightly, since much of our economic intuition is based on the very class of models that fall short so dramatically when confronted with financial data. It underscores the failure of paradigms central to financial and economic modeling to capture the characteristic that appears to make stocks comparatively so risky. Hence the viability of using this class of models for any quantitative assessment, say, for instance, to gauge the welfare implications of alternative stabilization policies, is thrown open to question* (Mehra and Prescott, 2003, p. 911).

Mehra and Prescott were referring to policies for macroeconomic stabilization, but their admonition applies equally to the use of IAMs to guide climate policy.

5. Insurance, precaution, and the contribution of climate economics

In the three preceding sections, we argued that most IAMs rely on an analytical framework that privileges immediate, individual consumption over future-oriented concerns; that the benefits, or avoided damages, from climate mitigation are both unpredictable in detail and intrinsically non-monetizable; and that the conventional economic view of technology misrepresents the dynamic, socially determined nature of technological change. Not much is left, therefore, of the standard economic approach and its ambitions to perform a competent cost-benefit analysis of climate policy options. In light of these criticisms, how should we think about policy options and the economics of climate change?

The optimal control approach to climate policy embodied in equation [1] above is not the only one proposed in the literature. For example, the early growth literature proposed the notion of the “Golden Rule” steady state growth path (Solow, 1970). In this simple model with the savings rate as the only policy variable, optimal growth is the path yielding the highest level of consumption per capita among all *sustainable* growth paths. Sustainable growth, in this context, is a path that does not sacrifice the consumption of future generations by depleting society’s capital (including natural capital) for the benefit of the present generation. In such a model, the market rate of interest is equal to the rate of growth of consumption. If the “willingness to pay” on behalf of future generations to avert environmental destruction is directly proportional to income, then the effective discount rate on the Golden Rule growth path is zero (DeCanio, 2003). The notion of the Golden Rule growth path has been generalized to “Green Golden Rule” growth, with different implications for the discount rate depending on the assumptions made about the interaction between the environment and the market economy (Chichilnisky et al., 1995; Bella, 2006).

Whether and how much people care about future generations can be represented in various ways—through the rate of subjective time preference in optimal growth models, through the weighting of different generations' welfare in overlapping generations models (Howarth and Norgaard, 1992; Howarth, 1996), through thought experiments in which the generations are able to transact with one another (DeCanio and Niemann, 2006)—and the results, not unexpectedly, will reflect the depth and strength of the intergenerational ties. The upshot of these alternative ways of characterizing the intergenerational decision-making problem is that the *normative assumptions that are made about how future generations are treated are as important as the technical details*. Not having happened yet, the future is unobservable; moreover, there are no reliable, universally accepted economic laws that shape our understanding of the future in the way that the laws of nature do for the physical reality of climate change. In addition, consciousness and intergenerational concern are influenced by social and political discourse. There is no fundamental reason, therefore, that social preferences should be immutable in the face of new knowledge that present-day consumption may adversely affect future generations.

One of the most interesting new areas of economic theory as applied to climate involves the analysis of deep uncertainty regarding future outcomes. If the probabilities of a range of possible outcomes were known, as in casino games or homework exercises in statistics classes, then there would be no need for a new theory; it would be a straightforward matter to calculate the expected value of climate outcomes and economic consequences. However, this approach is inadequate for managing the risks of climate change.[16] When probability distributions themselves are unknown, the problem of uncertainty is much more difficult to address. The combination of unknown probability distributions and potentially disastrous outcomes provides a strong motivation to purchase insurance against those disasters. As noted in a recent review of scientific knowledge about potential "tipping elements" of earth systems, "[s]ociety may be lulled into a false sense of security by smooth projections of global change….present knowledge suggests that a variety of tipping elements could reach their critical point within this century under anthropogenic climate change" (Lenton et al., 2008; see also Committee on Abrupt Climate Change, 2002). For example, uncertainty about the climate sensitivity, a key parameter in assessing the probability for ranges of potential equilibrium global temperature changes, is intrinsically resistant to improvements in scientific understanding (Roe and Baker, 2007).

Several economists working at the theoretical frontier have proposed new ways of dealing with these kinds of deep uncertainties (e.g., Gjerde et al., 1999; Chichilnisky, 2000; Hall and Behl, 2006; Dasgupta, 2008; Weitzman, 2007a,b, 2009). For example, in Weitzman's model

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[16] See also the paper in this volume by Yohe regarding a risk management context for climate policy.

(applicable to financial markets as well as climate change) people learn about the world through repeated experiences, but if the relevant structure of the world is changing rapidly or greatly enough, only the most recent experiences can be relied on to inform our future expectations. In this circumstance, we do not have sufficient history or experience to rule out the potential for catastrophic risks from climate change. As Weitzman argues, fine-tuning the estimates of the most likely level of climate damages is irrelevant; what matters is how bad and how likely the worst extremes of the possible outcomes are. The consequences of climate change are potentially so disastrous that conventional cost-benefit analysis is inadequate for policy-making.

Intuitively, this is the same logic that motivates the purchase of insurance, a precautionary decision that people make all the time. The most likely number of house fires that any given homeowner will experience next year, or even in her lifetime, is zero. Very few homeowners find this a compelling reason to go without fire insurance. Similarly, healthy young adults often buy life insurance to protect their children's future in the worst possible case. Residential fires and deaths of healthy young adults have annual probabilities measured in the tenths of one percent. In other words, people routinely insure themselves against personal catastrophes that could well have a lower probability of occurring than the worst-case climate catastrophes for the planet.[17] Chichilnisky and Sheeran (2009), using figures from the global reinsurance company Swiss Re, report that the world already spends 3.1 percent of global GDP – $250 per person annually – on non-life insurance premiums. This includes insurance policies to cover losses from natural disasters such as floods, fires, and typhoons, and man-made disasters such as plane crashes, rail disasters, and shipwrecks. Three percent of global GDP is what many IAMs estimate as the costs of mitigating climate change (Intergovernmental Panel on Climate Change, 2007c). If the world already spends this much to insure itself against low-probability but costly disasters, why would we not apply the same logic to potential climate change disasters (Chichilnisky and Sheeran, 2009)?

How would this perspective change our approach to climate economics and policy choices? Economics would no longer be charged with determining the optimal or utility-maximizing policy. Instead, a discussion of scientific information about catastrophic possibilities and consequences would presumably lead to the choice of maximum "safe" targets, expressed in terms of allowable increases in temperature and/or CO_2 levels. Once safe targets have been established, there remain the extremely complex and intellectually challenging tasks—for which the tools of economics are both appropriate and powerful—of determining the least-cost global strategy for achieving those targets, designing policies

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[17] Ironically, given the subsequent focus on cost-benefit analysis, one of the precursors of current IAMs appeared in a book titled, *Buying Greenhouse Insurance: The Economic Costs of CO_2 Emissions Limits* (Manne and Richels, 1992).

that effectively and with confidence meet the targets,[18] and sharing responsibility for the costs and implementation of that strategy.

This cost-effectiveness task, despite its daunting difficulty, is more manageable than the cost-benefit analysis attempted by policy optimizing IAMs, and the reduced scope avoids many of the problems we have discussed. Discounting is less of an issue because the costs of mitigation and adaptation, while still spread out in time, generally occur much sooner than the full range of anticipated damages. Precise estimation and monetization of benefits is no longer necessary; cost-effectiveness analysis takes the benefits side as fixed, or, in the language of economics, assigns an infinite shadow price to the constraint of meeting the chosen target—another way of saying that cost calculations are not allowed to override the prior choice of a safe standard.

6. Conclusions

There are two messages of fundamental importance here. The first is that policy makers should be skeptical of efforts by economists to specify optimal climate policy paths on the basis of the discounted utility framework embodied in the current generation of optimizing IAMs. These models do not embody the state of the art in the economic theory of uncertainty, and the foundations of the economic component of the IAMs are much less solidly established than the general circulation models that represent our best current understanding of physical climate processes. Not only do the IAMs used in climate economics entail an implicit philosophical stance that is highly contestable, they suffer from technical deficiencies that are widely recognized within economics. IAMs should not, therefore, be looked to as the ultimate arbiter of climate policy choices. Second, economists do have useful insights for climate policy. While economics itself is insufficient to determine the urgency for precautionary action in the face of low-probability climate catastrophes, or make judgments about intragenerational justice, it does point the way towards achieving climate stabilization in a cost-effective manner once designated decision makers have made informed value judgments about the actions society should take to limit the risks of climate change as understood and communicated by the scientific community.

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[18] The “tolerable windows approach” is one promising development in this direction. This methodology “concentrates on a few key attributes (e.g., acceptable impacts and costs) and provides an envelope for future action. Which course should be taken within the envelope?” (Toth et al. 2003, pp. 54-55). A special issue of *Climatic Change* (2003, nos. 1-2; see Toth 2003) contains a number of papers embodying this approach.

Abbreviations

CO_2: carbon dioxide
DICE: Dynamic Integrated model of Climate and the Economy
GCMs: General Circulation Models
GDP: Gross Domestic Product
GHGs: greenhouse gases
IAMs: Integrated Assessment Models
IPCC: Intergovernmental Panel on Climate Change
OECD: Organisation for Economic Co-operation and Development

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WORKSHOP PROCEEDINGS

Assessing the Benefits of Avoided Climate Change: Cost-Benefit Analysis and Beyond

Uncertainty and the Benefits of Climate Change Policies

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The complete workshop proceedings, including video of 17 expert presentations, this summary report, and individual off-prints of expert papers are available free of charge from the Pew Center on Global Climate Change at http://www.pewclimate.org/events/2009/benefitsworkshop.

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Uncertainty and the Benefits of Climate Change Policies[1]

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Abstract

This paper discusses the role of uncertainty in estimating the economic benefits of greenhouse gas emission reductions. First, we give a general overview of the range of approaches that analysts can use to account for uncertainty in benefit-cost analyses of climate change policies, and we discuss how to account for the "value of insurance" that a policy provides against potential climate catastrophes. A simple numerical example (given in an appendix) shows that uncertainty can in principle have a large influence on estimates of economic benefits. We then review some of the recent research by climate change economists that has begun to quantify this influence. We also give suggestions for short, medium, and longer term research. In the short and medium term, we recommend further synthesizing the recent research on the effects of risk and uncertainty on the benefits of climate policies and improving the currently available integrated assessment models to better account for these factors. In the longer term, we recommend expanding these models or developing new ones to incorporate the effects of learning, policy flexibility, and the value of additional information on the response of the climate system to greenhouse gas emissions and the economic consequences of the resulting climate changes.

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[1] The views expressed in this paper are those of the authors and do not necessarily represent those of the U.S. EPA. No Agency endorsement should be inferred

Introduction

Virtually all public policy decisions must be made in the face of uncertainty, and—at the risk of understatement—regulations to address climate change are no exception. Uncertainty can take many forms and can have different implications for the optimal stringency and structure of a policy, depending on the specifics of each case. The net effect depends on a variety of factors, including the relative risks of acting now versus waiting for more information, the potential for and costs of learning more about the impacts of the policy over time, and irreversibilities associated with ecosystem thresholds or mitigation activities (i.e. sunk benefits and costs [Pindyck 2000]). In the final analysis, uncertainty may increase or decrease the optimal stringency of a policy or weigh more heavily in favor of one type of instrument over others (such as cap and trade versus taxes), depending on the balance of these sometimes competing factors.

In this paper we address only a small part of this larger picture. Specifically, we focus on the effect of uncertainty on estimates of economic benefits of greenhouse gas emission reductions. First, we review the range of approaches that analysts can use to account for uncertainty in benefit-cost analysis. We perform some simple numerical calculations using a highly stylized model to show how uncertainty can influence the estimated benefits of climate policies, and we show how an expected utility framework can account for the "value of insurance" that a policy provides against potential climate catastrophes. Next, we review some recent research that has examined the effect of uncertainty on emissions reduction benefits, including our own work on climate response uncertainty and the shape of the damage function. We conclude with several recommendations for further research.

This paper is written for analysts, researchers, and especially managers and decision-makers who need to interpret and use the results of economic assessments in their deliberations over new climate change policies.

Tiers of Uncertainty Analysis

We begin by reviewing the range of approaches for addressing uncertainty in benefit-cost analysis in general and as applied to climate change policies in particular. This discussion loosely follows that in the Office of Management and Budget's Circular A-4 (OMB, 2003, p 41-42), though we elaborate further on the implications of conducting a formal uncertainty analysis in an expected utility framework.

The easiest approach for dealing with uncertainty is to simply describe it qualitatively, without addressing it explicitly in the quantitative analysis. More generously, we might say that the analyst can "average out the uncertainty" before estimating benefits and costs by plugging best-guess central point estimates of all uncertain parameters into the economic model. In doing this, the analyst tacitly accepts that the resulting point estimate of net benefits is only one among many possible outcomes. If the analysis ends here, the results are effectively treated as central best-guess estimates themselves. This approach is fairly common and will give an accurate estimate of the expected net benefits when the benefit function is (at least approximately) linear over the relevant ranges of all uncertain parameters.

If benefits are sufficiently non-linear over the relevant ranges, then the deterministic estimate may not be robust to the uncertainty in the input parameters. The next step, then, might be to conduct a sensitivity analysis, where the analyst varies each parameter over what are thought to be plausible ranges, based on the relevant scientific and economic research, and then records the effect of these variations on the net benefits. This provides a simple means of examining the response of the model to the key assumptions and often is useful for illustrating the importance of uncertainty to decision-makers and other consumers of the benefit-cost analysis. However, the more parameters that are varied at one time, the more difficult it is to interpret the results. Furthermore, the range of variations in model outputs illustrated in a sensitivity analysis may give little indication of their central tendency based on the relative likelihood of the many possible combinations of input parameters.

So the next logical step is to account for the uncertainty in all input parameters simultaneously. Known as Monte Carlo analysis, this can be done by specifying probability distributions for each parameter and then using computer simulation methods to construct a probability distribution for the estimated benefits.

It may seem that this is the final possible step in the progression of uncertainty analysis. However, it is possible to go further by framing the overall policy question in an expected utility framework. Under this approach, the analysis is structured to directly answer the question: Given all of the uncertainties regarding the input parameters and other assumptions of the model, what is the change in aggregate income with the policy that would make society just as well off as without the policy? In other words, what is the maximum amount of income society is willing to pay for the policy? In this approach, the analyst integrates over all sources of uncertainty within the economic model itself. The uncertainty is not “averaged out” before the parameters are plugged into the model, and the analyst does not simply construct a probability distribution for willingness to pay.

One key advantage of the expected utility approach is that it provides a natural way to account for potential low-probability high-impact outcomes. In effect, this framework can account for the value of the insurance that a policy would provide against the worst-case scenarios. This is an important consideration when analyzing greenhouse gas (GHG) emission reduction policies, since the potential for “climate catastrophes” is a key motivating factor for many citizens and decision-makers concerned about climate change (Keller et al., 2004; Hansen et al., 2007; Ramanathan and Feng, 2008). An evaluation framework that ignored this aspect of the problem would seem to be missing something essential.

A concrete illustration of the distinctions between the tiers of uncertainty analysis described above using a simple numerical example is provided in the appendix. The example shows that, under the typical assumption that climate change damages increase with temperature at an increasing rate, the deterministic analysis gives the lowest estimate of willingness to pay (WTP), the Monte Carlo approach gives a higher estimate of average WTP, and the expected utility approach gives the highest estimate. The magnitude of this "risk premium" will depend on both the level of uncertainty in the input parameters and the degree of risk aversion that is assumed.[2] Also, as emphasized by Weitzman (2009), the risk premium will depend crucially on the severity and probability of the worst-case outcomes.[3]

In light of the above, consider the Office of Management and Budget's (OMB's) guidelines. Circular A-4 indicates that the default assumption in a benefit-cost analysis should be one of risk neutrality. Specifically,

> "Emphasis on [expected values of benefits and costs] is appropriate as long as society is 'risk neutral' with respect to the regulatory alternatives. While this may not always be the case, you should in general assume 'risk neutrality' in your analysis. If you adopt a different assumption on risk preference, you should explain your reasons for doing so." (OMB, 2003, p 42).

This makes good sense for regulations that lead to small changes in risks. Even a risk averse individual would evaluate small risks based solely on their expected values as long as the risks are uncorrelated with the individual's income, since in this case the benefit function is approximately linear.[4] In contrast, the expected utility framework described in the preceding paragraphs and in the appendix explicitly assumes that society is not necessarily risk neutral with respect to climate change policies. The basic rationale is two-fold: 1) since the potential impacts of climate change are wide-spread—potentially global in scope, especially considering the worst-case catastrophic scenarios—the risks may be very large, and 2) the very high correlation among individual risks means that an effective risk-sharing arrangement is not possible (Arrow and Lind, 1970; Dasgupta and Heal, 1979, Ch 13). In other words, if the worst outcomes do come to pass then we may all be significantly impacted simultaneously, so there would be far less scope for spreading the risks. Furthermore, and on a more practical level, if the

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[2] In this paper we use the term "risk premium" to refer to the difference between estimates of willingness to pay based on an expected utility framework that explicitly accounts for parameter uncertainty and risk aversion and analogous estimates of willingness to pay based on a deterministic model that ignores uncertainty and risk aversion. This should not be confused with the "risk premium" in the finance literature that refers to the interest rate mark-up associated with risky investments.

[3] We should note that, as in all integrated assessment models of which we are aware, both the simple example given in the appendix and the simulation experiments in our previous work (Newbold and Daigneault 2009) ignore any potentially catastrophic risks of *reducing* GHG emissions. Such risks could arise, for example, from the possibility that elevated atmospheric stocks of GHGs could forestall a natural trend of decreasing global temperatures and therefore another ice age in the future (e.g., Ruddiman 2005). While such a scenario may be highly unlikely (very low probability), it may not be completely implausible (zero probability). If so, and if the damages from such a scenario also could be catastrophic, then a complete uncertainty analysis would include these potentially countervailing risks as well.

[4] A person is risk neutral if they are indifferent between prospects with the same expected returns, regardless of the variance of the possible outcomes. A person is risk averse if, of multiple prospects with the same expected returns, they prefer the one with the lowest variance in the possible outcomes. The relevance of the correlation between the riskiness of the prospect and the individual's income can be understood by imagining a case where the prospect is more likely to pay off high when the individual's income is lower (higher) than normal. In this case, the individual would be willing to pay more (less) for the prospect, all else equal. See Dasgupta and Heal (1979 Ch 13) for a more complete exposition.

changes in risks are in fact small then the expected utility framework will collapse to the equivalent of a risk-neutral analysis anyway.[5]

So far we have argued—and the appendix has illustrated—that uncertainty *can in principle* have a strong influence on the estimates of benefits for climate change policies. Next, we discuss some recent research that has begun to quantify these effects using economic integrated assessment models (IAMs).

Previous Research

A few recent studies have used Monte Carlo analysis or similar methods to account for uncertainty in economic climate assessment models, but so far the results have been decidedly mixed. For example, Roughgarden and Schneider (1999) constructed probability distributions over parameters of the damage function in DICE using results from a survey of experts and found that the average optimal carbon tax from a Monte Carlo simulation was around eight times higher than the point estimate from the standard DICE model. Pizer (1999) used a modified version of DICE and found that accounting for parameter uncertainty increased the estimated welfare gain from an optimal tax rate policy by roughly 25 percent compared to its deterministic counterpart. Tol (2003) used the FUND model and found that when accounting for uncertainty "the net present marginal benefits of greenhouse gas emission reduction becomes very large" and in one scenario appeared to be unbounded. Ceronsky et al. (2005) also used FUND and found "that incorporating [potential climate catastrophes] can increase the social cost of carbon [SCC] by a factor of 20." Hope (2006) used Monte Carlo analysis and found that the 5th percentile, mean, and 95th percentile of the probability distribution for the SCC were, respectively, \$4, \$19, and \$51 per ton of carbon. Uncertainty in the climate sensitivity parameter made the largest contribution to the variance of the SCC estimates. Nordhaus (2008) conducted an uncertainty analysis using the DICE model and concluded that "the best-guess policy is a good approximation to the expected-value policy." Weitzman (2009) showed that if the climate sensitivity distribution has a "fat-tail"—in other words, if the probability of ever higher temperature changes does not decline faster than the rate at which damages increase with temperature—then there is no bound on the willingness to pay for emissions reductions. And finally, Pindyck (2009) used a thin-tailed gamma distribution, including some versions with a significant right skew, but in most cases found only a modest risk premium.

In our own recent research, we focused on the effect of climate response uncertainty on estimates of economic benefits of GHG emissions reductions (Newbold and Daigneault, 2009). Specifically, we used Bayesian updating and model averaging to construct alternative probability distributions over the climate sensitivity parameter, which determines the equilibrium change in average global temperature to a doubling of the atmospheric greenhouse gas concentration (Andronova et al., 2007). We combined 28 confidence intervals for the climate sensitivity

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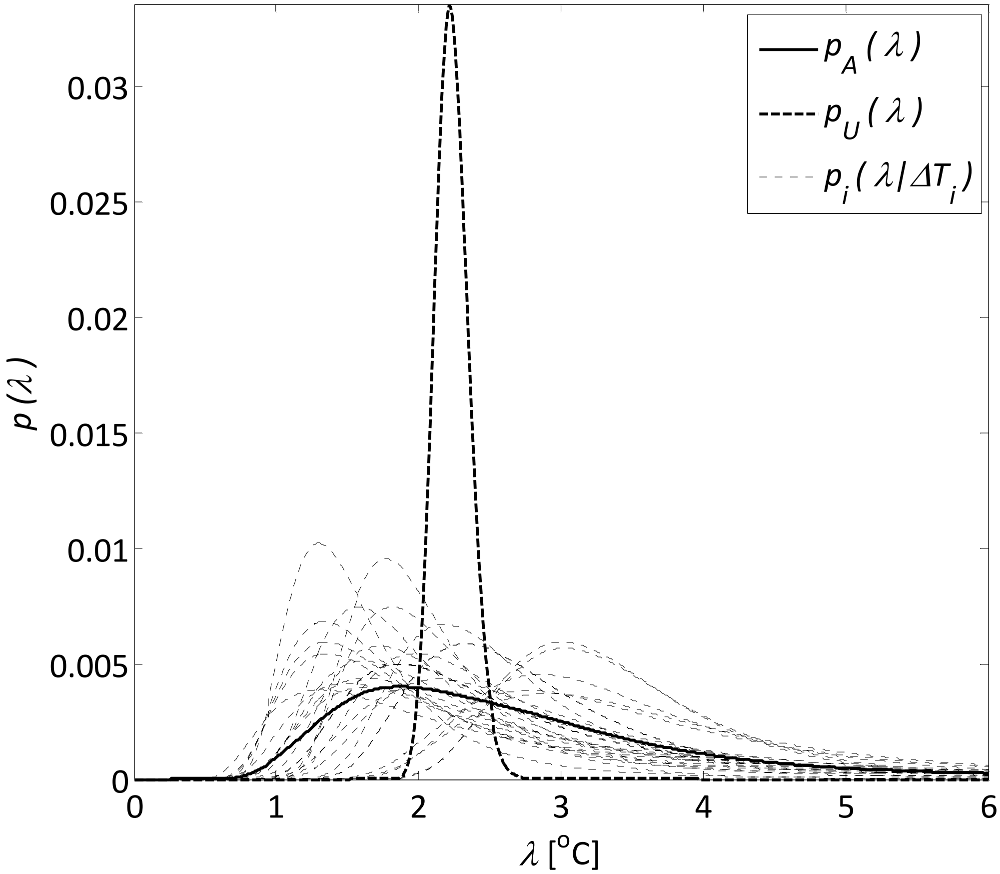
[5] The reader can use the model in the appendix to confirm this by assuming that the probability of a 1 degree temperature change is 100 percent. In that case, the estimates of willingness to pay differ by 0.1 percent or less.

parameter reported in 21 studies. Figure 1 shows the estimated probability distributions from each study and the two alternative composite distributions that we used to calculate willingness to pay in both a deterministic model and an expected utility model that incorporated uncertainty.

Figure 1. Roe and Baker (2007) probability distributions constructed from the 5th and 95th percentiles for the climate sensitivity parameter from 21 different studies (light dotted lines), the Bayesian model-averaged probability distribution function based on the average of the distributions (heavy solid line), and the Bayseian updated pdf based on the product of the distributions (heavy dotted line). From Newbold and Daigneault (2009).



The distribution constructed using Bayesian updating is centered around 2.2°C and is very narrow, so carrying this through the expected utility model gives results very close to the deterministic estimates of willingness to pay. However, this composite distribution is based on what seems like an overly-optimistic view of the climate science literature. It effectively assumes that the studies we combined can be treated as independent estimates using *new data* but the *same underlying model* of how the climate system works. So we also considered an alternative assumption, that these studies effectively used the *same underlying data* but a *different model* of how the climate system works, i.e., we combined the estimates using a “model averaging” approach. This assumption gives a much wider distribution for the climate sensitivity parameter.[6] Carrying this distribution through the expected utility model can give very large risk premiums, depending on the other parameter values. For example, we found that by using the Bayesian model-averaged composite distribution and an exponential damage function, the risk-adjusted willingness to pay for emissions reductions consistent with the optimal path from the DICE model (Nordhaus, 2008) was nearly five times larger than the deterministic willingness to pay.

One important take-home message from this research is the following: because IAMs that account for uncertainty can produce such a wide range of benefits estimates, it is crucial for decision-makers to understand the key ingredients of any integrated assessment model when interpreting its results. Until recently, much of the discussion in the literature on the economics of climate policy has focused on the "usual suspects," namely the discount rate and the expected damages at the central estimates of future temperatures. However, the simulation experiments described in detail in our previous work (Newbold and Daigneault, 2009) and in short form in the appendix suggest that part of the explanation for the divergent results summarized above may lie in the (possibly subtle) differences between the way each study characterized the climate response uncertainty and the shape of the damage function at high temperatures. Specifically, in addition to the usual suspects, we would emphasize the coefficient of relative risk aversion (see the appendix) and the magnitude and probability of the worst-case scenarios as important members of the short list of parameters likely to have the largest influence on the benefits estimates.[7]

Conclusions and Recommendations

In this final section we respond directly to the stated objectives of the Pew Center workshop that provided the occasion for this paper. Those objectives were "to develop a set of practical recommendations that decision makers can employ in the near-term, and to outline a research path to improve decision making tools over time." The recommendations we offer below are aimed mainly at researchers and analysts who develop and use integrated assessment models for the purpose of informing decision-makers in their deliberations over climate policies. These recommendations are based on our own current (and perhaps idiosyncratic) understanding of both the state of the art of climate policy benefits assessment and the needs of decision-makers. We will offer our suggestions in the form of short, medium, and longer term recommendations.

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[6] If this assumption is overly pessimistic, it is perhaps only modestly so since it is broadly consistent with the summary provided in the latest IPCC report (Hegerl et al. 2007).

[7] Importantly, the magnitude and probability must be considered simultaneously. See Sunstein (2007) for a discussion of the errors in public decision-making that can arise from placing undue attention on worst-case scenarios or paying no attention to them at all. Therein, Sunstein proposes a "Catastrophic Harm Precautionary Principle," which calls for close attention to both the magnitude and probability of a harm and allows for a "margin of safety for certain large-scale harms… akin to a purchase of insurance. Whether the margin is worthwhile depends on what is lost and what is gained by insisting on it." In the expected utility framework, the coefficient of relative risk aversion is the extra ingredient that allows for a systematic determination of the margin of safety (and of course the cost side of the ledger, not addressed in this paper, accounts for what is lost).

First, in the very short term (within one year or so), two useful tasks would be (1) to further synthesize previous research on the social cost of carbon (SCC), along the lines of meta-analyses conducted by Tol (2005, 2008), and (2) to construct a simple and transparent model for calculating the global and domestic SCC. Our experience has been that one of the first hurdles in discussing the economics of climate change with decision-makers is merely explaining the meaning of the SCC itself. A simple model constructed from first principles could be used as a tool for communication with decision-makers—in particular, helping to explain the proper interpretation and use of SCC estimates in a policy setting. It also could be used to produce rough estimates of the SCC and conduct sensitivity analyses and bounding exercises given any range of input assumptions that the user deems plausible. (We have in mind something similar to the simple model created by Tol and Yohe (2009) to examine *The Stern Review*.)

Second, for the medium term (between one and two years or so), a useful task would be to develop an improved IAM suitable for regulatory analysis alongside the standard models that federal agencies such as the Environmental Protection Agency typically use to estimate the costs of climate policies (e.g., ADAGE[8] and IGEM[9]). Such a model should build on existing IAMs that have been widely used in the climate economics literature (e.g., DICE, FUND, PAGE), but it also should add extensions and elaborations as dictated by the evolving demands of decision-makers. These might include adding currently omitted categories of benefits, a probabilistic structure that is suitable for uncertainty analysis (as in PAGE), and a capacity to incorporate risk aversion explicitly. In the process of building such a model, clear documentation should be developed simultaneously. In our experience, the more the model looks like a "black box," the less weight decision-makers are able to place on its results.

Our principal motivation for recommending that IAMs be extended to account for uncertainty and risk aversion is that, as discussed above, making fuller use of the expected utility framework provides a natural way to account for the high-impact, low-probability outcomes that are of primary concern to many citizens and decision-makers. Importantly, this approach forces us to bring these issues into the analysis in an explicit way while maintaining an ability to weigh the trade offs between the costs and benefits of incrementally more or less stringent policies. Partly because of the large uncertainties involved, some have recommended that economists should abandon their attempts to quantify the benefits of climate policies and rely mainly on cost-effectiveness analysis instead (e.g., Ackerman et al., 2009). We agree that cost-effectiveness analysis is useful in its own right for helping to identify the most affordable ways to meet different targets, but we also believe that IAMs can be expanded to account for uncertainty in such a way that they also can inform the choice of the target itself.

Third, for the longer term (on the order of three years and more), useful tasks would include (1) continuing to support basic research on the science of climate change and its potential impacts, and (2) continuing to improve IAMs by incorporating learning and policy flexibility.

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[8] http://www.rti.org/page.cfm?objectid=DDC06637-7973-4B0F-AC46B3C69E09ADA9

[9] http://www.hks.harvard.edu/m-rcbg/ptep/IGEM.htm

The importance of the first longer-term task is obvious. The weight of the scientific evidence on climate change, as summarized in the IPCC[10] and more recently the CCSP[11] reports, is substantial, but much remains to be learned. For example, as illustrated by the uncertainty surrounding the climate sensitivity parameter, there still is a very wide range of plausible future paths of global temperatures for any assumed path of GHG emissions. Even less well understood are the regional effects associated with each possible temperature path and the ensuing impacts on local ecosystems and economies. This is not to say that our knowledge is too meager to make informed policy decisions—limited information is not a sufficient condition to prefer the status quo policy. Rather, it is to say that there may be substantial value in gathering additional information in these areas. IAMs can only be as good as the scientific information that is fed into them.

The notion of the value of additional information leads to the second longer-term task. One dimension along which IAMs could be further improved is in their representation of learning and its effects on decision-making over time (e.g., Kelly and Kolstad, 1999; Fisher, 2001; Leach, 2007; Webster et al., 2008). This would require what ecologists and natural resource managers know as an "adaptive management" approach, which is a systematic framework for decision-making in the face of uncertainty that explicitly incorporates the feedbacks between learning and doing (e.g., Holling, 1978; Walters and Hilborn, 1978; Walters, 1986).[12] There are at least three advantages of this approach. First, it would in principle give more accurate estimates of the main quantity of interest: the value of emissions reduction policies in the face of uncertainty, potential learning, irreversibilities, and policy flexibility (or rigidity, as the case may be). Second, rather than a point estimate of the optimal policy it can produce an optimal policy *function,* which can be thought of a set of "contingency plans" covering the full range of possible outcomes. In other words, it can indicate how a policy instrument—such as a target, a tax, or an emissions cap—should be adjusted over time as the carbon stock grows, economic conditions change, and more scientific information accumulates. And third, it allows us to evaluate the trade-offs between the costs of emission reductions per se and the costs of collecting additional information to help reduce the uncertainties, so it can provide a unified framework for adjusting both our policy instruments and research expenditures over time.

In conclusion, our view is that economic methods, including both cost-effectiveness and benefit-cost analysis, can have a useful role in evaluating climate change policies. Nevertheless, researchers and analysts should strive to do a better job of explaining to decision-makers what their models can and cannot do. In particular, economists should better explain the meaning of the social cost of carbon estimates that their models produce so that decision-makers can make proper use of these figures in a policy setting. As an immediate corrective, economic analyses of climate change should clearly characterize the uncertainty in their results to avoid giving

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[10] http://www.ipcc.ch/

[11] http://www.climatescience.gov/

[12] The jargon varies among specialties. Economists will recognize this as a "real options" framework (e.g., Dixit and Pindyck 1996, Farrow 2004), and others will know it as a "stochastic dynamic programming" approach (e.g., Ross 1983).

decision-makers and the public a false impression of precision. And moving forward, researchers should continue to improve the existing models—and create new ones as needed—to aid in the development of "contingency plans" for the full range of possible outcomes. If we know anything with certainty, it is this: the probability that the future will unfold along any single deterministic forecast is vanishingly small.

Appendix

This appendix provides a simple numerical example to illustrate the distinctions between the tiers of uncertainty analysis described in the main text.

First, assume that "social welfare" or "utility," *U*, depends on aggregate income, *Y*, and the change in the average global temperature due to greenhouse gas emissions, *T*. To isolate the effect of risk aversion from time preference, we frame the problem as a static one, so we ignore the crucial dynamic dimension of the climate change problem in this example.

The willingness to pay, *WTP*, to prevent a change in temperature is the reduction in income with no temperature change that would make society just as well off as with the temperature change but no reduction in income. Formally, *WTP* is the solution to the following equation: $U(T,Y)=U(0,Y-WTP)$.

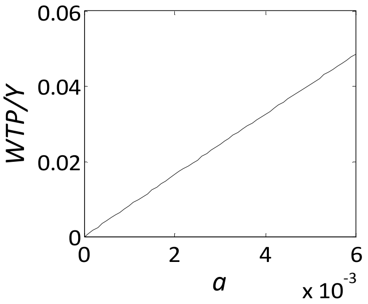
Second, assume that the damage from climate change (as a fraction of aggregate income), *D*, is an S-shaped function of the temperature change, specifically $D=1-\exp\left[-aT^b\right]$, where the parameters *a* and *b* determine the level and steepness of the damage function. Also assume that utility increases with income at a diminishing rate, specifically $U=Y^{1-\eta}/(1-\eta)$, where η is the elasticity of marginal utility (also referred to as the "coefficient of relative risk aversion"). Therefore, $U(T,Y)=\left[Y\left(1/\left[1+aT^b\right]\right)\right]^{1-\eta}/(1-\eta)$. These functional forms are consistent with those used in our previous work (Newbold and Daigneault, 2009).

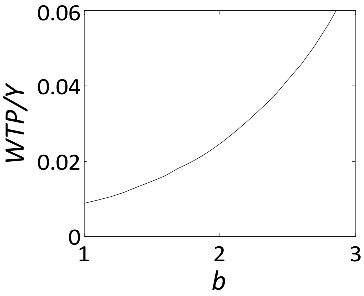
Third, assume that the best available economic research suggests that the parameter *a* is between 0 and 0.006 and *b* is between 1 and 3. Central values are considered more likely than extreme values, so the analyst assumes symmetric triangular distributions for both parameters. (For simplicity, we assume independence between *a* and *b*.) Also assume that the best available scientific research suggests that the temperature could change by either 1, 3, or 10 degrees Celsius, with probabilities 0.13, 0.85, and 0.02 respectively.

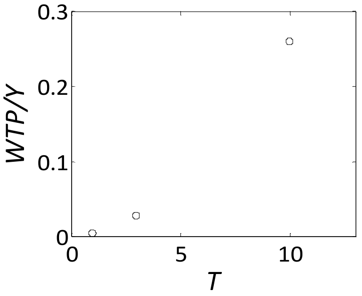
With these assumptions, the *deterministic estimate* of willingness to pay (as a fraction of income) is

$WTP/Y=1-\exp\left[-0.003\times 2.88^2\right]$ **= 0.0246.**

Next, to show the range of possible estimates of *WTP*, we conduct a *sensitivity analysis* over each uncertain parameter in turn, holding all other parameters at their expected values:

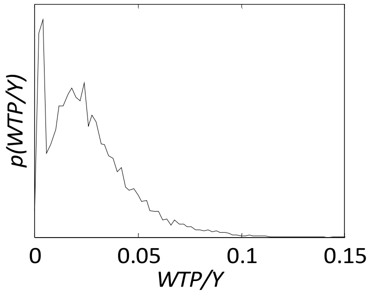






For example, the third graph above reveals that the consumption-equivalent damage from the worst-case scenario in this example is around 27 percent of current consumption.

Next, to construct a *probability distribution for WTP* we perform a Monte Carlo simulation, which involves drawing from the distributions of each uncertain parameter and re-calculating *WTP* for each draw. We then can plot the probability distribution of the results and calculate the expected value of *WTP* based on this distribution:

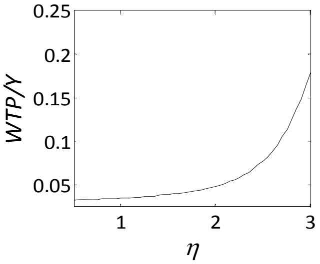


$$E\left[WTP/Y\right]=\int\int\int\left(1-\exp\left[-aT^{b}\right]\right)f(a)f(b)f(T)\,da\,db\,dT = \mathbf{0.0314}.$$

Finally, to calculate willingness to pay using an *expected utility approach*, we find the value of *WTP* that equalizes expected utility with and without the policy, i.e., $U(0,Y-WTP)= E\left[U(T,Y)\right]$. Using the above functional forms and assuming η = 2, this gives

$$WTP/Y=1-\left[\int\int\int\left(\exp\left[-aT^{b}\right]\right)^{1-\eta}f(a)f(b)f(T)\,da\,db\,dT\right]^{1/(1-\eta)}=1-E\left[U_{0}\right]^{1/(1-\eta)} = \mathbf{0.0446}.$$

Notice that the coefficient of relative risk aversion η appears in the calculation of *WTP* only when using the expected utility approach. The following graph shows the effect of η on *WTP*:



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WORKSHOP PROCEEDINGS

Assessing the Benefits of Avoided Climate Change: Cost-Benefit Analysis and Beyond

Addressing Climate Change through a Risk Management Lens

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Wesleyan University

May 2010

PEW CENTER ON Global CLIMATE CHANGE

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Addressing Climate Change through a Risk Management Lens

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Abstract

In the Summary for Policymakers of the Synthesis Report for its Fourth Assessment, the Intergovernmental Panel on Climate Change (IPCC) achieved unanimous agreement from signatory countries of the Framework Convention that, "Responding to climate change involves *an iterative risk management process* that includes *both adaptation and mitigation*, and takes into account *climate change damages, co-benefits, sustainability, equity and attitudes to risk*" (IPCC 2007c, pg 22; emphasis added). By accepting this key sentence, governments recognized for the first time, that their negotiations and associated policy deliberations must, individually and collectively, be informed by views of the climate problem drawn through the lens of reducing risk.

As new as this perspective might be for climate policy negotiators, risk-management is already widely used by policymakers in other decision making processes, such as designing social safety net programs, monetary policy, and foreign policy. Even though governments and some segments of the policy community are comfortable with the risk management paradigm, however, the climate change research and assessment community had heretofore been slow to catch on. This paper presents a first attempt to deconstruct the application of a risk-based paradigm to climate change by considering the critical phrases that are highlighted above, offering insights into what we do and do not know in each case.

Perhaps most importantly, the typical cost-benefit analysis used to make decisions in establishing regulations may not be fully appropriate for the climate problem because, to a large degree, many damages cannot be expressed monetarily and because uncertainty is so pervasive. To avoid being hamstrung by these fundamental complications, traditional policy analyses need to be supplemented by risk-based explorations that can more appropriately handle low-probability events and more easily handle large consequences calibrated in non-monetary metrics. In short, adopting a risk-based perspective will bring new clarity to our understanding of the diversity and complexity of the climate problem.

Introduction

Since the Synthesis Report of the Fourth Assessment Report (IPCC, 2007c) was approved by the Intergovernmental Panel on Climate Change in November 2007, much of the world's attention has focused on the economic costs of mitigation, species extinctions, extreme weather events, and other impacts that were highlighted in the previously approved report of Working Groups II and III (IPCC, 2007a & 2007b). Although these are important examples of the society and nature's vulnerability to climate change, the key policy development of the Fourth Assessment has received little attention: in a few paragraphs that appear toward the end of the Summary for Policymakers of the Synthesis Report, governments accepted ***risk*** as the unifying theme of this and future assessments. Because the world's governments unanimously approved the Summary for Policymakers word by word, they have all agreed that risk—not just impacts or their derivative vulnerabilities—matters most to them as they consider how to respond to the climate problem. As an expression of this paradigm shift, governments embraced a fundamental insight of the Fourth Assessment:

> *Responding to climate change involves an iterative risk management process that includes* ***both adaptation and mitigation****, and takes into account climate change* ***damages, co-benefits, sustainability, equity and attitudes to risk****.*
> (IPCC 2007c, pg 22; emphasis added)

Governments are beginning to understand that the risk associated with any possible event depends both on its likelihood and its potential consequences. This is the definition of risk that finance ministers have been using for decades, so it is not surprising that many governments' delegations understand the concept. Perhaps the only surprise was that it took so long for governments to recognize that they should look at climate change through the same lens through which they view social safety-net programs, monetary policy, and foreign policy.

Although governments and some segments of the policy community may be comfortable with the risk management paradigm, the climate change research and assessment community has heretofore failed to catch on. If researchers are to contribute further to the assessments that are the foundations of global policy deliberations, they must make rapid progress in providing policy-relevant, rigorous, scientific insight into how to make sense of the IPCC's conclusion quoted above.

This paper presents a first attempt to deconstruct the paradigm by taking each italicized phrase in turn and offering insights into what we do and do not know in each case. We know quite a bit about some of these critical phrases, and future research agendas will focus on applying, extending, and communicating that knowledge. For others, however, research into new approaches is required. Section 1 begins with a brief discussion of how *iterative* processes might be applied to the climate arena. Section 2 focuses attention on the need for supplementing traditional cost-benefit approaches with *risk-management* techniques. The insights offered here are amplified in Sections 3 and 4 by underscoring the roles of *both adaptation and mitigation* in a risk-reduction portfolio and by highlighting the boundaries of our understanding of the *benefits and co-benefits* of such a portfolio. Section 5 offers some preliminary thoughts about the roles of *sustainability, equity, and attitudes toward risk* in evaluating and synthesizing the value and costs of future iterative policy decisions. Finally, the concluding section reviews what we do and do not know about how to apply analytic techniques to the synthetic conclusion.

1. "Iterative"

Although climate change is a long-term problem that will require sustained policy action for a century or longer, it is unlikely that we will be able to set climate policy today for the entire 21st century. Many uncertainties are so profound that they will not be resolved soon and, in some cases, may only be resolved in hindsight. A classic example of this conundrum is climate sensitivity—the increase in global mean temperature that is caused by a doubling of carbon dioxide concentrations from pre-industrial levels. Current understanding, as reported in IPCC (2007a, pg 65), puts the likely range of this critical parameter at 2 – 4.5 ^{o}C, but higher values are possible and it is widely accepted that timely reductions in this uncertainty are unlikely.[1] As reported in Roe and Baker (2007), for example, "the probability of large temperature increases" is "relatively insensitive to decreases in uncertainties associated with the underlying climate processes." Allen and Frame (2007) responded by arguing that it was pointless for policy makers to count on narrowing this fundamental uncertainty. As a result, a policy response that delays immediate action in favor of waiting for the results of a crash research program to narrow the range is not viable. Moreover, we should not anticipate that we will be able to set long-term policies in concrete at any time in the foreseeable future. It follows that we must begin to construct a process by which *interim targets and objectives* will be informed by *long-term goals* in ways that necessary adjustments can be made in an efficient manner (e.g., Yohe et al., 2004). This is a simple and logical conclusion, but difficult to make operational.

Domestic and international banking and financial systems provide some evidence that iterative policy-making can be accomplished on a macro scale (e.g., Stiglitz and Walsh, 2005; chapters 32 and 33). For example, central banks frequently set trajectories for growth in the money supply when they expect normal economic activity over a foreseeable future; they work within an announced time period that defines precisely when they expect to make the next round of policy decisions. Since they do not have exact control over the money supply, however, central banks also reserve the right to intervene

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[1] IPCC (2007a) describes "the equilibrium climate sensitivity [as] a measure of the climate system response to sustained radiative forcing. It is not a projection but is defined as the global average surface warming following a doubling of carbon dioxide concentrations. It is *likely* to be in the range 2°C to 4.5°C with a best estimate of about 3°C, and is *very unlikely* to be less than 1.5°C. Values substantially higher than 4.5°C cannot be excluded, but agreement of models with observations is not as good for those values."

earlier than anticipated if the money supply climbs above or falls below clearly described thresholds that define acceptable levels of variability. Central banks can also monitor exchange rates in exactly the same way. In both cases, actors across the economy know exactly how the central bank will conduct its analyses in anticipation of making scheduled policy adjustments; that is, they can anticipate much of what will happen during those adjustments and begin to make appropriate changes in their own behaviors in advance of the policy change. These actors also understand what the banks will do if unanticipated adjustments are initiated by crossing the trigger threshold; that is, they can also detect early warning signs so that they can begin to respond in advance of these more unexpected events. In other words, transparency in the process can lessen the costs of planned or unplanned policy adjustments.

The experiences of these monetary structures suggest at least three evaluative criteria that can be applied to the climate arena: (1) keep long-term target options available for as long as possible by adopting hedging strategies to inform near-term actions and identifying downstream adjustment thresholds, (2) minimize the adjustment costs of regularly implemented adjustments, and (3) minimize administrative complexity in both by making them as transparent and as predictable as possible.

Events in the financial markets that marked the second half of 2008 clearly indicate that difficulties can still arise, especially when policy levers and well understood monitoring mechanisms break down. Central banks may have been monitoring the money supply, inflation rates, and exchange rate fluctuation in the early part of 2008, but it would seem that they were not keeping track of complexity in financial instruments that spread enormous risk across a range of unsuspecting and otherwise debt-burdened citizens and institutions.

Potentially unforeseen difficulties are perhaps even more ubiquitous and dangerous in the climate arena. The enormous uncertainty that still clouds our understanding of the climate system means that climate policy must be implemented while simultaneously monitoring impacts and vulnerability of human and natural systems. Even when we understand specific climate processes very well, persistent and potentially profound uncertainties about impacts can produce fuzzy thresholds of dangerous interference across key vulnerabilities that cannot all be calibrated in dollars. Some are best left in terms of "millions of people at risk from coastal storms" or changes in the return-times of the current 100-year flood. In other words, risks are potentially large and the possibility of a "bail-out" might be quite low. Insights drawn from our experience with monetary policy show us, however, that this complexity should not be a source of paralysis. Instead, they show the fundamental need for iterative policies that are designed both to hedge against potential calamities (i.e. lower their likelihoods with full understanding that there are no guarantees) and to adjust efficiently in response to new information about the climate and economic systems as well as performance against near-term goals.

2. "Risk management process"

Having recognized that pervasive uncertainty in our understanding of both the climate system and future political-social-economic development pathways requires iterative climate responses, we must now turn to framing the underlying analysis in ways that can inform such an approach. Here we contrast conventional benefit-cost techniques designed to determine the "optimal" policy with broader risk-management techniques designed to hedge against uncertain but potentially high-consequence outcomes and allow for mid-course adjustments as needed.

Beginning perhaps with Nordhaus (1991), the dynamic long-term version of the standard benefit-cost paradigm has been the mainstay of economic analyses of climate policy (particularly on the mitigation side). In applying this approach, researchers track economic damages that would be associated with climate change and costs that would be associated with climate policy over time scales that extend decades or centuries into the future. They calibrate these damages and costs along scenarios of economic development and resource availability that represent a range of possible (but unpredictable) futures. The damages and costs are disaggregated across countries and regions to varying degrees by different researchers, and both are discounted back to present values. In this final step, estimates of the present value of benefits and costs are highly sensitive to uncertain natural parameters (e.g., climate sensitivity) and uncertain policy parameters (e.g., the assumed discount rate, which is extremely sensitive to attitudes toward risk, attitudes toward inequity, and inter-temporal impatience, as discussed below).

Pointing out that some benefits (and even some costs) cannot be monetized, many researchers and commentators have become increasingly critical of this approach.[2] In response, practitioners have opened the door to tracking benefits and costs in terms of alternative, non-economic metrics, although such metrics have yet to be applied to regulatory policy.[3] They have also recognized problems with specifying appropriate discount rates, coping with uncertainty, and accommodating the profound distributional consequences of climate change.[4] Early in 2009, President Obama signed Executive Order 13497 instructing the Director of the Office of Management and Budget to review these issues with advice from regulatory agencies. While progress has been slow at the federal level, this action opens the door further to non-quantified costs and benefits expressed in

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[2] Critiques of relying too heavily on limited benefit-cost analyses include Tol (2003), Yohe (2004, 2006), and Ackerman et al. (this volume).

[3] For example, Circular A-4 [White House (2003)] was issued by the Office of Management and Budget to update long-standing instructions that defined the standards for "good regulatory analysis" – exercises that work from statements of need and explorations of alternative approaches to produce evaluations of the "benefits and costs – quantitative and qualitative – of the proposed action and the main alternatives…" The Circular leads with an explicit "presumption against economic regulation." Most of the text, though, is dedicated to illuminating "best practices" for circumstances in which intervention is deemed warranted. It begins by highlighting benefit-cost and cost-effectiveness analyses as the "systematic frameworks" within which to identify and to evaluate the likely outcomes of alternative regulatory choices. The Congressional Budget Office (2005) amplified these points.

[4] See the paper by Rose in this volume.

non-monetary terms, including maintaining risk thresholds, being considered for regulatory design. Indeed, City of New York adopted this approach when it started to think about how to protect its enormous public and private infrastructure from growing climate risk; see NPCC (2009) for details.

As suggested by the IPCC (2007c), risk-management techniques can explicitly accommodate many (but not all) of these thorny issues.[5] Its most straightforward applications to climate change begin, as elsewhere, with the statistical definition of risk – the probability of an event multiplied by its consequence. In benefit-cost approaches, all consequences are calibrated directly as anticipated economic outcomes that are expressed in units of currency. In these applications, any dollar lost or gained in one possible outcome is worth the same as any other dollar lost or gained in any other outcome. It follows that decision-makers need only worry about expected dollar gains or losses regardless of how good or bad any particular outcome might be.[6] Risk management approaches expand the range of analytic applicability by allowing consequences to be calibrated in terms of more general welfare metrics. These metrics may depend on the same outcomes as before, but they make it clear that one dollar in one possible outcome is not necessarily worth the same as one dollar in another possible outcome. Metrics that reflect aversion to risk, for example, hold that an extra dollar gained in a good outcome is worth less, in terms of welfare, than an extra dollar lost in a bad outcome. It follows that the extremes of possible outcomes matter in these cases, and it is in these contexts that people buy insurance and/or adopt hedging strategies against especially bad outcomes—even if such strategies fail in a benefit-cost analysis. They do so because hedging increases expected welfare (computed over the welfare implications of the full range of possible outcomes) even though it reduces the expected dollar value of the associated outcomes.[7]

What do we know about how to apply this insight in the climate arena? According to the IPCC (2007a), we know "unequivocally" that the planet is warming. We are now "virtually

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[5] The foundations for the results that follow can be found in Raiffa and Schlaiffer (2000).

[6] To be precise, let the range of possible outcomes be calibrated by $\{X_1, \ldots, X_n\}$ where the subscripts indicate financial values in n possible future states of the world. A benefit-cost approach looks only to calculating the expected outcome across these futures. That is, if $\{\pi_1, \ldots, \pi_n\}$ represent the subjective likelihoods of each possible outcome, then expected benefit-cost calculations would focus attention exclusively on $E\{x\}$ ⍰ $\Sigma \pi_i \cdot X_i$.

[7] To continue with the notation of footnote 5, risk-analysis lets the consequences be calibrated in terms of welfare and not just outcomes. It follows that the relevant measure of the range of consequences is $\{U(X_1), \ldots, U(X_n)\}$ where U(-) is the welfare metric. In this case, decision makers worry about expected welfare and not expected outcome; i.e., they would focus attention on $E\{U(X)\}$ ⍰ $\Sigma \pi_i \cdot U(X_i)$. If they are averse to risk (so U(-) increases with X at a decreasing rate), then they would buy insurance even though the premiums they pay lowers every possible outcome. Why? Because insurance guarantees that they will be compensated to some degree should a really bad outcome (a really low value for X_i) materializes. In other words, they willingly sacrifice expected economic value calculated across all possible outcomes to reduce the pain that they would feel in the (potentially unlikely) event that a single bad outcome might occur; and they are so willing because doing so increases their expected welfare. Hedging is a variant on the same theme in which decision-makers sacrifice expected economic value to invest in some action that works to reduce the likelihood that a bad extreme event might occur. Both results can be derived directly from the observation that risk aversion means that $E\{U(X)\} < U(E\{X\})$.

certain" that the climate is changing at accelerating rates. We also know with "very high confidence" that anthropogenic emissions are the principal cause. We even have evidence that anthropogenic climate change was the strongest contributor to the conditions that created the 2003 heat wave across central Europe that caused tens of thousands of premature deaths (Stott et al., 2004; IPCC, 2007b). We also know from the dire consequences of the 2003 European heat wave, the 2004 Asian Tsunami, and Hurricane Katrina in 2005,[8] that both developing and developed countries are susceptible to the types of events that are expected to occur more often and with greater intensity in the future because of climate change. This knowledge alone is sufficient to establish the serious risks of climate change and the need to respond in the near-term in ways that will reduce future emissions and thereby ameliorate the pace and extent of future change. Indeed, looking at uncertainty through a risk-management lens makes the case for near-term action through hedging against all sorts of climate risks—risks that can be denominated in terms of economic damages as well as other indicators, including more widespread hunger, water stress, or greater hazards from coastal storms. It then follows from simple economics that action should begin immediately in order to minimize the expected cost of meeting any long-term objective.

As discussed previously, monetary policy provides a real-world illustration of how hedging strategies have been employed at a macro scale. At a 2003 symposium on "Monetary Policy and Uncertainty: Adapting to a Changing Economy,"[9] Chairman of the Federal Reserve Board Alan Greenspan, illustrated the point:

> *For example, policy A might be judged as best advancing the policymakers' objectives, conditional on a particular model of the economy, but might also be seen as having relatively severe adverse consequences if the true structure of the economy turns out to be other that the one assumed. On the other hand, policy B might be somewhat less effective under the assumed baseline model … but might be relatively benign in the event that the structure of the economy turns out to differ from the baseline. These considerations have inclined the Federal Reserve policymakers toward policies that* ***limit the risk*** *of deflation even though the baseline forecasts from most conventional models would* ***not project such an event.*** (Greenspan, 2003, pg. 4; emphasis added)

Indeed, none of the models that informed Federal Reserve policy would even put a probability on the chance of deflation. The Board simply knew that it was not zero and that they did not want the economy to endure the consequences. The Chairman expanded on

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[8] Note that these events need not be linked to climate change to expose the underlying vulnerabilities to similar events that would be linked to climate change in the future. For example, although the Asian tsunami was caused by an earthquake, it simulated a storm surge that might be associated with a strong tropical cyclone.

[9] Monetary Policy and Uncertainty: Adapting to a Changing Economy: A symposium sponsored by the Federal Reserve Bank of Kansas City, Jackson Hole, Wyoming, August 28 - 30, 2003.

this illustration in his presentation to the American Economic Association (AEA) at their 2004 annual meeting in San Diego:

> *...the conduct of monetary policy in the United States has come to involve, at its core, crucial elements of risk management. This conceptual framework emphasizes understanding as much as possible the many sources of risk and uncertainty that policymakers face, quantifying those risks when possible, and assessing the costs associated with each of the risks. ... ... This framework also entails, in light of those risks, a strategy for policy directed at maximizing the probabilities of achieving over time our goals...* (Greenspan, 2004, pg. 37; emphasis added)

Clearly, these views are consistent with an approach that would expend some resources over the near term to avoid a significant risk (despite a low probability) in the future. Indeed, the Chairman used some familiar language when he summarized his position:

> *As this episode illustrates (the deflation hedge recorded above), policy practitioners under a risk-management paradigm may, at times, be led to undertake actions intended to provide insurance against especially adverse outcomes.* (Greenspan, 2004, pg. 37; emphasis added)

Can our current understanding of the climate system support a similar approach to managing the risks of climate change? At the very least, we need some information about consequences of climate change that we would like to avoid and some insight into the sensitivity of their likelihood to mitigation. These are fundamental questions that must be addressed before proceeding.

Many authors have provided insights to some or all of the requisite components, i.e., estimates of probabilities of specific outcomes and quantifications or the associated vulnerabilities. Some have, for example, compared the costs of mitigation with the corresponding changes in climate risks:

- Mastrandrea and Schneider (2004) used the simplified integrated assessment model DICE to assess the costs of avoiding dangerous climate change as defined by assumptions drawn from the IPCC Third Assessment Report (IPCC, 2001a, 2001b).[10]
- Webster et al. (2003) used an integrated model of intermediate complexity to quantify the likelihoods of global warming futures in 2100, beginning with projections of population, economy and energy use.
- Jones (2004a, 2004b), Wigley (2004) and Jones and Yohe (2008), present frameworks that probabilistically relate stabilized CO_2 concentrations with equilibrium temperature, although these studies stopped short of relating their results to either the costs of mitigation or the benefits of avoiding damages.

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[10] For background on integrated assessment models, see the paper by Mastrandrea in this volume.

- Others have begun to consider the role of future learning in informing risk assessment. Brian O'Neill edited an entire volume of papers designed to explore the role of learning in setting long-term mitigation strategies (O'Neill, 2008).
- Schlesinger *et al.* (2006) adopted a more focused approach by tracking the likelihood of a collapse of the Atlantic thermohaline circulation (THC) over the next one or two centuries under a variety of mitigation assumptions using three alternative representations of uncertainty in climate sensitivity. Zickfeld and Bruckner (2008) followed with an investigation of the implications of alternative emissions corridors on the same THC risk profile using an alternative ocean model.

Taken together, these studies show progress in tracking the potential efficacy of mitigation in reducing the likelihood of very negative outcomes.

The concept of certainty equivalence is used in risk analysis to convert consequences calibrated in welfare terms into financial terms. Essentially, certainty equivalence accounts for risk aversion by providing an estimate of how much people would be willing to pay to avoid the risky situation.[11] It has also been employed to inform climate change mitigation decisions in cases where the relative likelihoods of various possible futures can be analyzed. Stern *et al.* (2006 and 2007) expressed damages in terms of losses in certainty equivalent per capita consumption discounted over 200-years. Using the uncertainty analysis capabilities of the simplified integrated assessment[12] model PAGE2002, the authors accommodated enormous variability in per capita consumption across 1000 model runs by computing mean expected discounted utility without and with climate change for three different damage calibrations. Certainty equivalents with and without climate change were then computed for each calibration; i.e., the authors calculated the level of per-capita consumption which, if it were to grow with certainty at 1.3 percent per year (an assumed "natural growth rate"), would achieve a level of discounted utility exactly equal to the expected discounted utilities just defined. The economic values of global damage attributable to climate change damages under alternative calibrations were then taken to be the differences between certainty equivalents with and without climate change for the three calibrations. In their simplest form, these computed differences are simply estimates of the fraction of current per capita consumption that the representative citizen would be willing to pay to eliminate all of the climate risk captured by the underlying analysis.

Stern et al. (2006) estimated what their representative citizen would be willing to pay to avoid all damages associated with three damage calibrations, but they provided no

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[11] The certainty equivalent of a risky situation is implicitly defined as the outcome that would, if it could be guaranteed, achieve a level of welfare or utility that is equal to the *expected welfare* or *utility* calculated across all possibilities. Returning to the notation of footnotes 5 and 6, the certainty equivalent outcome X_{ce} is defined implicitly as the solution to the equation $U(X_{ce})$ ⍰ $E\{U(X)\}$. Since $X_{ce} < E\{X\}$ for risk-averse decision-makers, the difference between a certainty equivalent and an *expected outcome* (i.e., $E\{X\} - X_{ce}$) therefore represents an estimate of what people would be willing to pay to avoid the risky situation altogether. In addition, differences in certainty equivalents for two distributions of outcomes can be used to track what people would be willing to pay to reduce uncertainty. For a recent application of this approach, see Newbold and Daigneault in this volume.

[12] For background on integrated assessment models, see the paper by Mastrandrea in this volume.

information about what their representative citizen would be willing to pay for various levels of emission reductions and their associated reductions in damages. Tol and Yohe (2009) worked to fill this gap using a much simpler model; Table 1 shows their results. Notice in the first row that the unregulated path is calibrated to match the Stern baseline – a 5.3 percent reduction in certainty equivalent per capita consumption from climate change. Corresponding levels of residual damage, expressed comparably in terms of certainty equivalence along cost-minimizing mitigation pathways, are then reported for concentration thresholds ranging all the way down to 400 ppm. Since all of these residuals are positive, none of the considered mitigation targets obviates the need for adaptation.

Table 1: Estimates of residual economic damage along least-cost mitigation pathways from the Stern et al. (2006) baseline expressed in terms of percentage changes in certainty equivalent per capita consumption relative to scenarios along which climate does not change. *(Source: Tol and Yohe, 2009)*

Atmospheric Concentration	Δ Certainty Equivalent Per Capita Consumption
unregulated	-5.3 percent
750 ppm	-3.8 percent
700 ppm	-3.4 percent
650 ppm	-3.0 percent
600 ppm	-2.6 percent
550 ppm	-2.2 percent
500 ppm	-1.7 percent
450 ppm	-1.3 percent
400 ppm	-0.8 percent

To summarize, we know that humanity's greenhouse gas emissions are changing the climate in ways that are likely to be detrimental to society and that some of the consequences could be catastrophic. We also know that the timing and severity of these changes are imprecisely associated with particular socioeconomic and emissions pathways. To be brutally honest, pervasive uncertainty about the physical and economic consequences of climate change undermines the credibility of economically optimal policies that emerge from traditional benefit-cost calculations. Since there is good evidence to suggest that getting the "optimal policy" wrong could be extremely expensive, it follows from straightforward economics that a complementary approach aimed at managing/reducing risk is required. It is important to recognize that hedging policies that emerge from the risk management approach would sacrifice a little in expected utility, but the payoff would be reductions in the likelihoods of unacceptable declines in general welfare – declines that would result if the optimal policy should fail.

3. "Both Adaptation and Mitigation"

The discussion has thus far framed mitigation as a mechanism by which climate risks can be reduced. This initial focus is appropriate because adaptive capacity can be overwhelmed even within the middle range of projected warming in developed and developing countries alike (IPCC, 2007b, Chapter 20). However, adaptation to unavoidable change is also required since we would be committed to another 0.6ºC of warming even if greenhouse gas emissions had fallen permanently to zero in the year 2000 (IPCC, 2007b). It is therefore essential to consider the roles of both adaptation and mitigation in setting long-range climate stabilization goals and translating those goals into short-term objectives (in terms of, for example, emissions peaking points and the timing of adaptation investments). To make the synthetic statement of the IPCC (2007c) operational, we must also show how adaptation can be engaged in an iterative process designed to manage risk and how the need for adaptation can be influenced by investment in mitigation.

Since these issues have not yet received much attention, we will offer a simple applied example that focuses attention on the vulnerability of New York City to severe coastal storms as a proof of concept. In this example, the 100-year coastal flooding anomaly for New York City (as judged by FEMA in 2005) is chosen to represent how such vulnerability might be experienced. It builds directly on recent work by Kirshen et al. (2008) in which return times of the current "100-year" flooding event are correlated with prospective levels of sea level rise. It is important to note that the effects of changing intensities or frequencies of coastal storms were not considered. Only the effect of rising sea levels on storm surges associated with storms that now occur more frequently were considered (for example, the current 25- or 50-year anomalies that will, with rising sea level, portray inundation patterns now associated with the 100-year anomaly).

Alternative trajectories of future sea level rise around New York City were derived from 4 alternative emissions scenarios reported, along with subjective probabilities of their relative likelihoods, in Yohe et al. (1996) across 9 alternative climate sensitivities.[13] Figure 1 shows the results of superimposing the resulting probability-weighted sea level rise scenarios on the Kirshen results for flood return intervals. Given this information, a decision-making planner who reported that a 40-year return time was the lower bound of his or her comfort zone could see an 80 percent chance that this threshold would be breached within a 2025 planning horizon with virtual certainty beyond 2035. This realization could easily trigger any number of adaptive responses that could range from significant investment in protection to planned retreat from the sea (highly unlikely in downtown Manhattan, but more likely for some more residential and exposed communities). If, however, our planner were comfortable after having taken some preliminary protective action, with a lower return time like 20 years for the current 100-year anomaly, then the likelihood of falling below this lower threshold would be a more tolerable 20 percent in 2025 and 30 percent in 2030. The subjective likelihood of crossing the critical return time threshold would, though, jump to more than 60 percent by 2035. It follows that the original urgency of the more risk-averse planner would be diminished, but

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[13] The climate sensitivity distribution applied here is drawn from Yohe et al. (2004); it is a discrete representation of the distribution reported in Andronova and Schlesinger (2001).

not by much; put another way, adaptation might work for a short while, but it would not be sufficient over the long-term.

Figure 2, drawn from Yohe (2009) displays some evidence about the sensitivity of the return time of the 100 year flooding anomaly to alternative mitigation pathways for the year 2050. The unabated plot adds some detail to the 2050 distribution recorded in Figure 1. The IPCC (450) mitigation scenario adds about 10 years to the median return time – roughly equivalent, according to Figure 1, to a 10 or 15 year delay in crossing the 50-50 risk threshold. Notice, however, that the more cost-effective WRE mitigation pathway (see Wigley et al., 1996), which allows emissions to peak later at the expense of sharper reductions thereafter, results in a smaller time delay than the earlier-acting IPCC scenario. Two insights from these results are that (1) slowing emissions buys more time for planning, financing, and implementing adaptation, and (2) the timing of emissions reductions (i.e. earlier vs. later peaking) for given stabilization concentration (e.g., 450 ppm CO_2-e) affects how much time the mitigation effort buys. Hence, the timing of mitigation efforts can influence the urgency with which adaptation might be pursued. Different levels of mitigation effort could even alter which adaptation options would be feasible

It should be clear from this preliminary work that risk profiles can portray a wide range of vulnerabilities over time even if those vulnerabilities cannot be expressed in terms of a single (monetary) metric. They can, therefore, be enormously valuable in considering and prioritizing investments in adaptation across multiple sectors and/or multiple locations. They can also be used to display the sensitivity of risks, with and without adaptation, to various mitigation pathways, although integrating the content of many individual risk profiles and scaling them up to the macro scale at which mitigation decisions are made remains problematic. A collection of vulnerability studies drawn from a wide sample of key vulnerabilities can nonetheless provide those decisions with information that is hidden in simple calculations of aggregate economic benefits. Such collections could thereby inform political deliberations about what might constitute “dangerous anthropogenic interference with the climate system” more fully.

Figure 1: The Relative Likelihoods that the Return Time of the 2005-calibrated 100-Year Anomaly Will Be Smaller than the Specified Planning Horizon in Selected Years. Any point on any line indicates, with its vertical location and for the identified year in the future, the likelihood that the return time of the 100-year storm will be smaller than the value identified by its horizontal location. For example, the third triangle up the red line shows that by 2035 it is more than 60 percent likely that the return time will be less than 20 years.

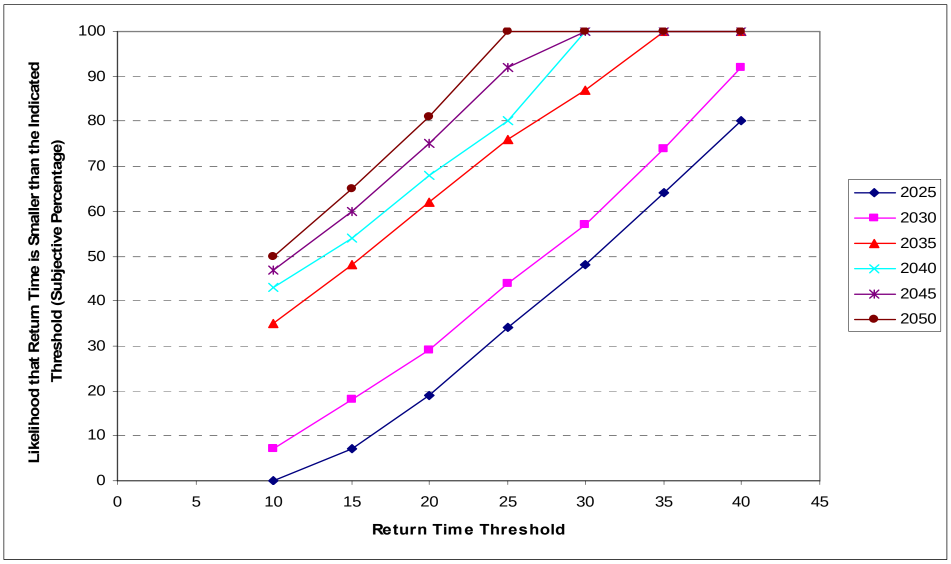
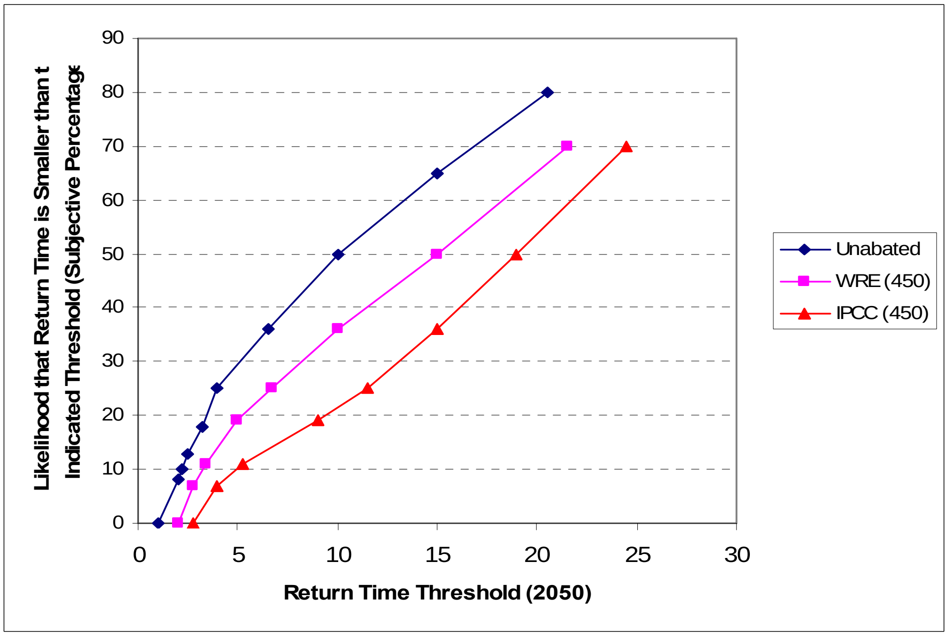


Figure 2: The Relative Likelihoods that the Return Time of the current 100-Year Anomaly Will Be Smaller than the Planning Horizon in 2050. The lines indicate the likelihood that the return time of the 100-year storm along unabated and two mitigation trajectories will be smaller than the indicated threshold in 2050; both stabilize concentrations of greenhouse gases at 450 ppmv in CO_2 equivalents along two different emissions trajectories. The slower pace of early reductions along the more cost-effective WRE trajectory reduces the efficacy of mitigation to slow the reduction in return times.



4. “Damages and co-benefits”

We turn now to consider metrics by which the damages of climate change, the costs of mitigation, and the potential for co-benefits across the two have been expressed. The first subsection indicates that existing estimates of economic damages from climate change have failed to address many of the dimensions of possible non-marginal climate impacts (that is, impacts that involve large and/or sudden changes). The second describes the “key vulnerabilities” identified from the current literature in Fourth assessment Report of the IPCC (2007b); the point here is that many of these vulnerabilities cannot be monetized (that is, they can only be calibrated in non-monetary metrics). A final subsection discusses the latest contribution by Martin Weitzman to the debate – a theoretical result that questions our ability to accommodate profound uncertainties that stretch the underlying probability distributions into regions where extreme and ambiguous consequences might occur.

4.1 Missing impacts

The matrix displayed in Figure 3, derived from a similar figure in Downing and Watkiss (2003), summarizes the state of the art in analyzing the economic impact of climate change and therefore the economic benefit of climate policy; it also appears in Yohe and Tirpak (2008) from which much of this subsection is drawn. The columns are divided vertically by the degree to which the complication of uncertainty in climate change science is captured by benefits analysis. They begin with coverage of projections of relatively smooth climate change trends (e.g., average temperature, sea level rise), move on to considerations of the bounded risks of extreme weather events (e.g., large-scale precipitation events and droughts) and climate variability along those trends, and end with representations of possible abrupt change and/or abrupt impacts. The rows are divided horizontally by the degree to which the corresponding impacts can be calibrated in monetary terms. They begin on the left with coverage of market impacts, move on to considerations of non-market impacts, and end with evaluations of socially contingent impacts (e.g. multiple stresses leading to famine and migration) across multiple metrics that cannot always be quantified in economic terms.[14]

Taken as a whole, the diagram suggests that much of the existing research has focused on market impacts along relatively smooth scenarios of climate change; i.e., most of our knowledge about the economic costs of climate change has emerged from *area 1* alone. In this context, researchers have noted the importance of site-specificity, the path dependence of climate impacts and the adaptive capacity of various systems. While coverage is greatest

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[14] The entries in the matrix are meant to be illustrative; and they are not meant to suggest the exclusive location of particular sectors like agriculture and forestry. There are, for example, impacts in those sectors derived from projections of long-term trends. They are shown in the bounded risk category to demonstrate additional and perhaps dominate sensitivity to climate driven variability and extreme weather events.

in *area 1*, this diversity of context means that coverage of even market-sector impacts is far from comprehensive.

Figure 3: Coverage of Existing Economic Analysis of the Impacts of Climate Change Related Risks. Most existing studies have been limited to market-based sectors, though a few have moved beyond region I to include non-market impacts along projected trends (region IV), bounded risks in market and non-market sectors (regions II and V) and abrupt change to selected market sectors (region III).

	Uncertainty in Valuation →			
		Market	**Non Market**	**Socially Contingent**
Uncertainty in Predicting Climate Change ↓	**Projection (e.g., sea level Rise)**	**I** Coastal protection Loss of dryland Energy (heating/cooling)	**IV** Heat stress Loss of wetland	**VII** Regional costs Investment
	Bounded Risks (e.g. droughts, floods, storms)	**II** Agriculture Water Variability (drought, flood, storms)	**V** Ecosystem change Biodiversity Loss of life Secondary social effects	**VIII** Comparative advantage & market structures
	System change & surprises (e.g. major events)	**III** Above, plus Significant loss of land and resources Non-marginal effects	**VI** Higher order Social effects Regional collapse	**IX** Regional collapse

Source: Yohe and Tirpak (2008), derived from Downing and Watkiss (2003).

Although a limited literature exists for economic impacts in areas II – V, no study has attempted a comprehensive analysis, either for lack of data or for the inability to monetize damages for certain categories of impacts.[15] The existing literature has almost nothing to say about impacts and vulnerability calibrated in the non-market impacts of abrupt change in and the multiple metrics of socially contingent impacts (*areas VI – IX*). Through these socially contingent vulnerabilities, climate impacts in one place (e.g., the developing countries) can be felt elsewhere (e.g., in the United States or the rest of the developed world). All calculations of the potential benefits of climate policy completely ignore these elements of climate risk. It does not necessarily follow, however, that attempts to calibrate these vulnerabilities in terms of economic damages should be the focus of new research. Indeed, it is here, perhaps most critically, that multiple metrics of climate-related risk must be accommodated so that our policy discussions are more fully informed about what might happen.

Despite these shortcomings in the coverage of our impacts analysis and concerns about our understanding of the climate system, researchers and, policy makers are now required to use the results of analyses that emanate largely from *area I* of Figure 3 to conduct assessments of optimal climate policies and to compute estimates of the social cost of CO_2 and other greenhouse gases. These social costs are estimated by tracking the damage caused over time by releasing an additional ton of a greenhouse gas like CO_2 into the atmosphere and discounting those estimates back to the year of its emission. That is to say, the social cost of carbon represents the “marginal cost” of carbon emissions; alternatively, it represents the “marginal benefit” of a unit of carbon emissions reduction.

Estimates of the social cost of carbon that are currently available in the published literature vary widely. IPCC (2007b) was informed by an early survey conducted by Tol (2005), which reported that fully 12 percent of then available published estimates were below $0 (i.e. the impacts of climate change were estimated to produce a net positive economic benefit). Their median was $13 per ton of carbon, and their mean was $85 per ton. Tol (2007) offers an updated survey of more than 200 estimates. His new results show a median for peer-reviewed estimates with a 3 percent pure rate of time preference and without equity weights (i.e. no recognition that a dollar of harm effects the poor more than the rich) of $20 per ton of carbon with a mean of $23 per ton of carbon. Moreover, he reports a 1 percent probability that the social cost of carbon could be higher than $78 per ton given the same assumptions; and he notes that the estimates increase rapidly with lower discount rates—one of the primary reasons why the range of estimates of the social cost of carbon is so large.

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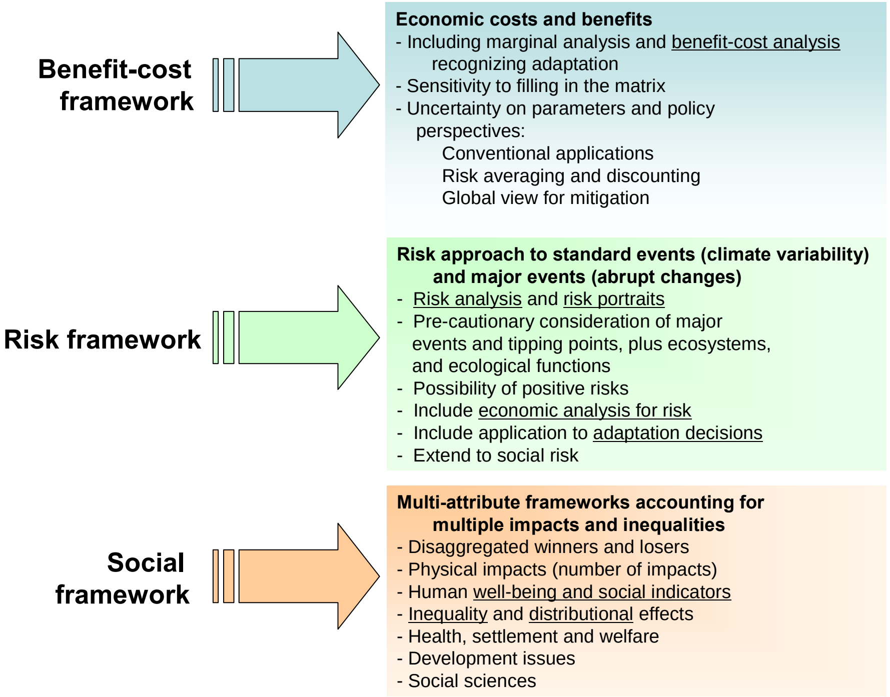
[15] For further discussion of damage estimates for *areas II – V* in Figure 3, see the appendix at the end of this paper and the paper by Mastrandrea in this volume.

Figure 4: Multiple Analytic Frameworks for Climate Policy Research. Characteristics of various analytical approaches are highlighted. General applicability increases from top to bottom with the prospect of supporting analyses of damages and co-benefits that would, were they available, begin to populate the lower right side of the matrix depicted in Figure 3 and thereby improve our understanding of the full range of issues. *(Source: Jones and Yohe, 2008).*



Economic costs and benefits
- Including marginal analysis and benefit-cost analysis recognizing adaptation
- Sensitivity to filling in the matrix
- Uncertainty on parameters and policy perspectives:
  - Conventional applications
  - Risk averaging and discounting
  - Global view for mitigation

Risk approach to standard events (climate variability) and major events (abrupt changes)
- Risk analysis and risk portraits
- Pre-cautionary consideration of major events and tipping points, plus ecosystems, and ecological functions
- Possibility of positive risks
- Include economic analysis for risk
- Include application to adaptation decisions
- Extend to social risk

Multi-attribute frameworks accounting for multiple impacts and inequalities
- Disaggregated winners and losers
- Physical impacts (number of impacts)
- Human well-being and social indicators
- Inequality and distributional effects
- Health, settlement and welfare
- Development issues
- Social sciences

The estimates above largely exclude impacts populating areas II-IX in Figure 3, yet Tol's survey provides evidence that assumptions about how to include even partial coverage of non-market damages can dominate estimates of market damages. Assumptions about what might emerge from more thorough investigations of *areas IV* through *VI* of Figure 3 are therefore critical, even if inference from a limited number of studies is suspect. Perhaps even more troubling is the observation that few if any of the estimates recognize abrupt change (*areas III, VI,* and *IX*); and none venture into anything contained in the right-hand column (*areas VII* through *IX*). Our current inability to populate the lightly shaded regions of Figure 3 with credible analyses undermines our ability to compute the social cost of carbon, and thus the economic benefit of climate policy, with any confidence.

Figure 4 offers some insight into how some of the light shaded areas in Figure 3 might be accommodated analytically. After characterizing traditional benefit-cost and risk-based approaches in its first two rows, the last row draws attention to a third type of analysis: multi-criteria approaches designed to illuminate vulnerabilities across the socially contingent impacts called out by the right column of Figure 3. Although practical approaches have yet to be developed, it is likely that much of this analysis would identify thresholds of socially unacceptable climate change or climate stress. To the extent that this is true, the risk profiles described above for the risk management perspective could be applied. Multiple and potentially non-monetary metrics have already been accommodated, and many have been expressed in terms of the likelihood of crossing critical thresholds set by natural systems. Putting humans into the business of defining comparable thresholds based on their values, institutions, and state of knowledge adds complication to the analysis, but risk profiles can accommodate these metrics, as well.

4.2 Key Vulnerabilities and Multiple Metrics

The authors of Chapter 19 of IPCC (2007b) seized on the content of Figure 3 (as portrayed in Chapter 20) to underscore the need for multiple impact metrics as they examined and identified "key vulnerabilities" to climate change.[16] They began their work by arguing how key vulnerabilities could be identified on the basis of a number of criteria that could be found in the literature: magnitude, timing, persistence/reversibility, the potential for adaptation, or lack thereof, distributional aspects, likelihood and 'importance' of the impacts. Leaving the last criterion, "importance", to the eye of the decision-making beholder, they offered an illustrative list based on not only their expert assessments of the literature, but also the insights offered by the authors of the sectoral and regional chapters of IPCC (2007b).

The content of their work has been most effectively communicated through changes in five aggregate "reasons for concern" first developed for and presented in the IPCC's Third Assessment Report (IPCC, 2001a, 2001b). These metrics, only two of which are calibrated predominantly (but no longer exclusively) in terms of economic measures, include:

- *Risk to unique and threatened systems* speaks to the potential for increased damage to or irreversible loss of unique and threatened systems such as coral reefs, tropical glaciers, endangered species, unique ecosystems, biodiversity hotspots, small island states, and indigenous communities. There is new and stronger evidence of observed impacts of climate change on unique and vulnerable systems (such as polar and high mountain communities and ecosystems), with increasing levels of adverse impacts as temperatures increase further. An increasing risk of species extinction and coral reef damage is projected with higher confidence now than in the Third Assessment Report (IPCC, 2001b) as warming proceeds.
- *Risk of extreme weather events* tracks increases in extreme events with substantial consequences for societies and natural systems. Examples include increase in the frequency, intensity, or consequences of heat waves, floods, droughts, wildfires or tropical cyclones. There is now new and stronger evidence of the likelihood and likely impacts of such changes, such as the IPCC (2007b) conclusion that it is now "more likely than not" that human activity has

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[16] Vulnerabilities, here, are defined as is now most usual in terms of exposure to anticipated impacts and associated sensitivities that can be ameliorated by exercising available adaptive capacity. Since all three of these components of the vulnerability (exposure, sensitivity and adaptive capacity) are site-specific and path-dependent, an ability to accommodate the diversity noted in subsection 2.1 remains critical.

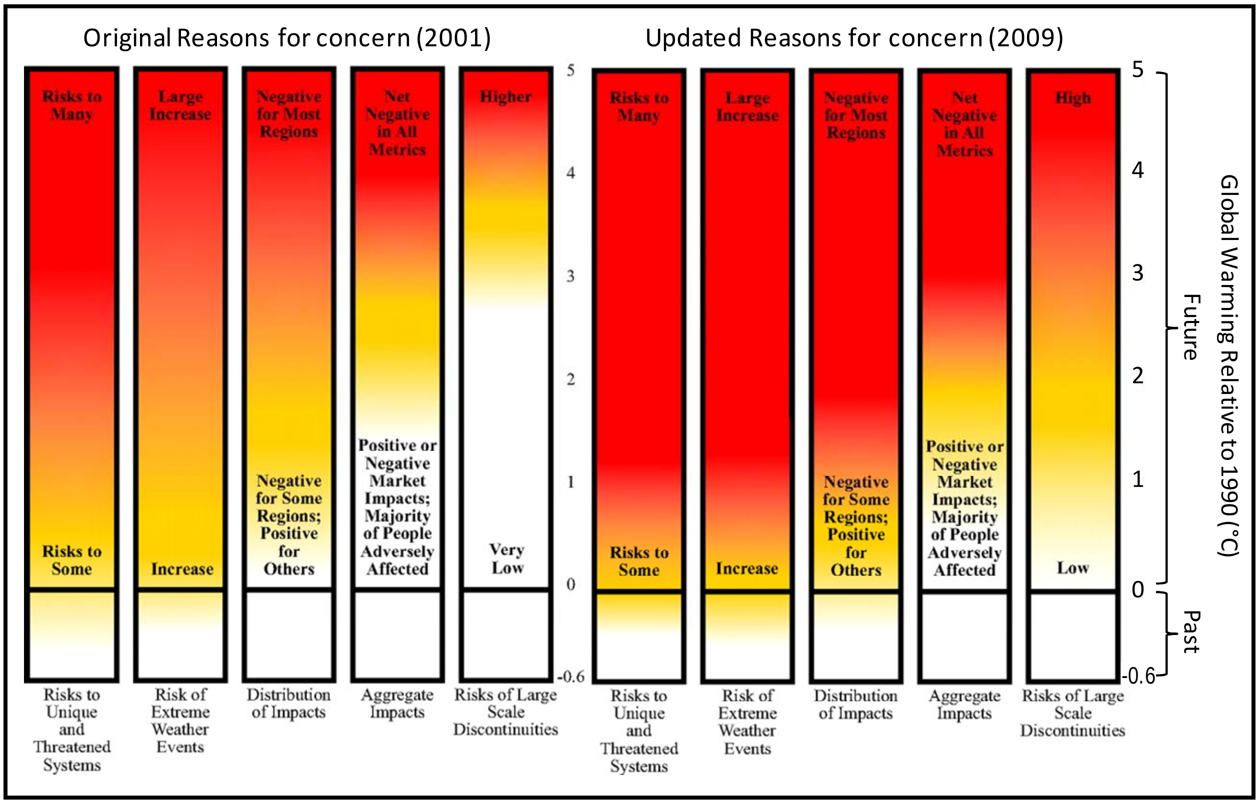
contributed to observed increases in heat waves, intense precipitation events, and intensity of tropical cyclones.

- Distribution of impacts and vulnerabilities concerns disparities of impacts, i.e. whether the poor are more vulnerable than the wealthy. Some regions, countries, and populations face greater harm from climate change while other regions, countries, or populations would be much less harmed and some may benefit. New research finds, for example, that there is increased evidence that low-latitude and less-developed areas in, for example, dry areas and mega-deltas generally face greater risk than higher latitude and more developed countries. Also, there will likely be disparate impacts even for different groups within developed countries.
- *Aggregate damages* cover comprehensive measures of impacts from climate change. Impacts distributed across the globe can be aggregated into a single metric such as monetary damages, lives affected, or lives lost. New evidence supports the conclusion that it is likely there will be higher damages for a given level of increase in average global temperature than previously thought, and climate change over the next century will likely adversely impact hundreds of millions of people.
- *Risk of large-scale discontinuities* represents the likelihood that certain phenomena (sometimes called singularities or tipping points) would occur, any of which may be accompanied by very large impacts, such as the melting of major ice sheets. For example, there is now better understanding that the risk of additional contributions to sea level rise from melting of both the Greenland and Antarctic ice sheets may be larger than projected by ice sheet models assessed in the IPCC (2007a, 2007b) and that several meters of additional sea level rise could occur on century time scales.

Figure 5 displays the differences in the "burning embers" thresholds for these Reasons for Concern between the 2001 version published in the Third Assessment Report (IPCC, 2001a, 2001b) and a more recent interpretation by many of the same authors (Smith et al., 2009). In general, the authors judge that significant risks, depicted by red coloring in the figure, occur at lower temperatures than previously assumed. These authors have revised their perceptions of risk based on the past decade of observations showing that both developing and developed countries alike are more vulnerable to extreme weather impacts than previously realized and also from observations that the climate system may react more strongly and abruptly to warming.

The critical insights to be derived from this discussion is that the notion of risk (as the product of probability and consequence) has been firmly ensconced in the discussions of impacts and benefits of climate policy and that investigations of how to respond to climate change have begun to recognize the diversity of potential vulnerabilities beyond the narrow economic spectrum of aggregate and regional impacts that can be calibrated in currency.

Figure 5. Risks from climate change, by Reason for Concern – 2001 compared with 2007. Climate change consequences are plotted against increases in global mean temperature (°C) after 1990. Each column corresponds to a specific Reason for Concern (RFC). The left panel displays the RFCs from the IPCC Third Assessment (IPCC, 2001a, 2001b). The right panel presents updated RFCs as described in Smith et al. (2009) and represents additional information about outcomes or damages associated with increasing global mean temperature. The color scheme depicts progressively increasing levels of risk, and should not be interpreted as representing "dangerous anthropogenic interference," which is a value judgment. The historical period 1900 to 1990 warmed by about 0.6°C and led to some impacts. This figure addresses only how risks change as global mean temperature increases, not how risks might change at different rates of warming. Furthermore, it does not address when impacts might be realized, nor does it account for the effects of different development pathways on vulnerability.



4.3. Another Reason for Concern from Martin Weitzman

At first blush, Weitzman (2009) adds even more complexity to the valuation problem by showing that profound uncertainty about fundamental parameters like climate sensitivity can overwhelm any economic estimate of climate damages. In practice, his result follows directly from our inability to observe the extreme ranges of climate impact distributions with enough frequency to learn anything useful about their relative likelihoods. He concludes that uncertainty will dominate any calculation of expected climate damage because even systematic learning over time about the critical variables is never strong enough to keep expected marginal damages finite; and so his result argument clearly casts doubt on results derived from economic calibrations of damages avoided by mitigation. On the positive side, his result indicates that the value of some types of information is far greater (and perhaps infinitely greater) than the value of other information. It can therefore offer some guidance on where to devote scarce research resources in climate and policy science. Moreover, offers sound theoretic footing for a generalized risk-based approach designed explicitly to examine and clarify the definition of tolerable climate change.

To explore the implications of his result a little more fully, it is appropriate to put it more squarely into the context of what we know about climate change. Tol (2003), for example, worked within a benefit-cost framework that recognized multiple regions with and without equity weighting. His simulations across a wide range of possible futures noted the small but non-zero probability that utility consequences of marginal impacts could grow infinitely large in one or more regions where some "not-implausible" climate futures could drive economic activity to subsistence levels. As long as these regions were given non-zero weight in the expected welfare calculation, their plight would dominate the policy calculus because expected marginal damages would approach infinity

Yohe (2003) suggested that the problem highlighted in Tol (2003) could be overcome by implementing a second policy instrument designed to maintain economic activity above subsistence levels everywhere – a foreign aid program designed simply to prevent economic collapse anywhere in real time, even if collapse happens to be the result of an extreme climate impact someplace in the world. Tol and Yohe (2007) examined this suggestion within the original modeling framework and found that, with sufficient aid, the issue of infinite marginal damage could be avoided. While this work did not envision globally distributed extremes as reflected in Weitzman's characterization of uncertainty surrounding climate sensitivity, it nonetheless suggested that timely social or economic interventions that effectively "lop off the thick tails" of regional climate impacts could undercut the power of his result. If, however, the catastrophe were felt globally, then virtually any insurance or compensation scheme based on transfers from well-off to less well-off regions would break down because non-diversifiable risk would be unbounded. It is here, therefore, that a generalized precautionary principle – the logical implication of Weitzman's insight – is an appropriate frame from which to derive a potential response. Yohe (2009) goes so far as to suggest that it is here that the analogy to hedging against deflation in the conduct of monetary policy carries the most weight. Indeed, Weitzman has recently used this analogy to argue for spending up to 3 percent of GDP per year for hedging insurance (The Economist, 2009).

Yohe and Tol (2009) nonetheless suggest that the policy community should instead ask the research community to develop greater understandings of the fundamental processes in areas other than climate sensitivity – processes that produce catastrophic *impacts* from whatever climate change happens to materialize, for example. Even if they cannot rely on the scientific community to reduce the range of possible scenarios in the temperature domain, they could ask it to (1) explore the triggers of more regional catastrophe, (2) identify the parameters of fundamental change that define those triggers, (3) contribute to the design of monitoring mechanisms that can track the pace of change relative to these triggers, and (4) conduct small- and large-scale experiments in models, laboratories and perhaps the real world to learn more about the relevant processes.

Risk profiles of the sort displayed above can also provide some critical insights in into the practical applicability of Weitzman's warning about thick tails in the climate system. One can easily see in Figure 1, for example, that any decision-maker concerned with protecting New York City from the risks associated with increases in the frequency of the current 100-year flooding anomaly would become acutely concerned within the next decade or two. One can, as well, see that this concern does not necessarily depend on a thorough understanding of the distribution of climate sensitivity. Put another way, Weitzman's insight could be less relevant in cases where climate futures driven by the middle of the sensitivity distribution produce intolerable impacts a little bit further into the future than the Weitzman-esque extremes of the same distribution. Why worry about the low-probability extremes when even high-probability outcomes could be intolerable a few years later?

To be clear, the point of focusing on the links between physical climate processes and potentially catastrophic impacts at a regional level is not to dismiss the need for hedging through mitigation against catastrophic globally-distributed futures that might be housed in the extremes in distributions of variables like climate sensitivity. It is, instead, to inform investments in adaptation that complement global hedging on the mitigation side of the policy equation.

5. "Sustainability, Equity and Attitudes toward Risk"

Sustainability, equity and attitudes toward risk are cross-cutting themes that permeate throughout everything noted above. The ability of the research community to accommodate their implications into analytical techniques is not well developed, but it is not difficult to demonstrate that they matter and should therefore be considered in risk management and policy making.

With regard to sustainability, for example, there are synergies across the determinants of adaptive and mitigative capacities and the precursors of sustainable development. Because they match to a large degree, initiatives designed to promote progress with respect to the Millennium Development Goals can support climate policy. The news is not all good, though, because the potential for conflicting objectives is real and diversity confounds general insights. With regard to the later, whether or not the links between an economic intervention (or an adaptation) and its desired outcomes are strong, weak, or actually run counter to expected benefits is essentially an empirical question in nearly every instance. And while it is widely known that unabated climate change can impede progress toward achieving the Millennium Development Goals, for example, there is such a thing as dangerous climate policy – adaptive or mitigative programs that retard economic growth and thereby undercut the ability to develop sustainably (e.g., Tol and Yohe, 2006).

The relative importance of equity and attitudes toward risk can, perhaps, best be displayed formally by exploring the dual roles that they play in determining the proper discount rate to be applied to monetized damages. In this regard, it is essential to remember that climate change is a long-term problem even if the appropriate approach to designing policy is to work iteratively. Greenhouse gas emission reductions over the near-term would mitigate future damages, but they would do little to alter the present climate and/or the present rate of change in climate impacts. Moreover, mitigation must continue well into the future if long-term objectives are to be achieved and long-term progress is to be sustained. In a cost-benefit framework, therefore, the discounted costs of emission abatement must be justified by the discounted benefits of avoided impacts in the future. In a risk-management framework, the discounted costs of abatement must be minimized subject to the constraint of achieving the desired reductions in climate risk. It follows from either approach, therefore, that any statement about the desirability of climate policy necessarily contains a value judgement about the importance of future gains relative to present and future sacrifices.

To understand why, it is sufficient to realize that people discount future consumption for two reasons. First, they expect to become richer in the future, and so they expect an additional dollar to buy less happiness then than an additional dollar would buy today. In economics, the amount of happiness (or utility) an additional dollar can buy is called the marginal utility of consumption. The interest rate at which a dollar would need to grow to entice its owner to invest it rather than spending it today is called *elasticity of marginal utility of consumption*. Second, people are impatient, preferring to consume now rather than later, regardless of future circumstances. The interest rate at which an invested dollar would need to grow to entice its owner to invest in the future rather than spending impatiently is called the *rate of pure time preference*.

Together, these two motives for discounting the future drive the so-called Ramsey discount rate (denoted by r below) that was designed to sustain optimal saving over time (Ramsey, 1928). The Ramsey equation therefore consists of three components:

$$r = \rho + \eta g$$

where ρ is the rate of pure time preference, g is the growth rate of per capita consumption, and η is the elasticity of marginal utility of consumption.

The rate of pure time preference calibrates inter-temporal trading so that individuals who anticipate constant levels of consumption from one period to the next would be willing to sacrifice one dollar of present consumption if he or she would be compensated with *\$(1 + ρ)* of *extra consumption* in the next period. Higher values of ρ reflect higher degrees of impatience because greater compensation would be required to compensate for the loss of \$1 in current consumption.

Consumption levels need not be constant over time, of course, and the second term in the Ramsey equation works the implication of this fact into this trading calculus. While g measures the growth rate of material consumption, ηg reflects the growth rate of happiness measured in terms of underlying personal utility. If consumption were to climb by $g \cdot 100$ percent from one period to the next, then each future dollar would be worth $g \cdot \eta \cdot 100$ percent less (assuming no impatience so $\rho \equiv 0$). It follows that our individual would consider sacrificing one dollar in current consumption only if he or she could be compensated by an amount equal to $\$(1 + g\eta)$ in the future.

In contemplating welfare-based equivalence of consumption over time, it is now clear that this trading-based accommodation of growing consumption works in exactly the same way as the pure rate of time preference in defining the rate at which the future needs to be discounted. Put another way, if one considered empirical estimates for both ρ and η, then both parameters should play equally important roles in determining the appropriate discount rate. Perhaps because “impatience” is intuitively clear while the role of the “elasticity of marginal utility of consumption” is not, the debate over how to discount the future has focused undue attention on ρ almost to the exclusion of η.

Climate change is not only a long-term problem; it is also a very uncertain problem with the potential of reducing future consumption (risk), and a problem that differentially affects people with widely different incomes (inequity). The rate of pure time preference ρ speaks only to the first characteristic of the climate policy problem – the intergenerational time scale. The elasticity of marginal utility of consumption, the parameter η, speaks to all three characteristics (intergenerational equity, the risk of uncertain but negative outcomes, and differential impacts on people with different incomes). First, it indicates precisely the degree to which an additional dollar brings less joy as income increases for one individual. Second, it can be interpreted as a measure of the utility of an extra dollar for a rich person relative to the utility of an extra dollar for a poor person. This is why η is occasionally referred to as the parameter of inequity aversion. Third, it can be interpreted as a measure of how increases in consumption improve welfare more slowly than reductions in consumption diminish welfare. This is why η is also referred to as the parameter of risk aversion; and it is in this role that it helps explain why risk-averse people buy insurance.

As suggested in the opening paragraph of this final section, the purpose of this brief discussion is not to explain exactly how sustainability, equity, and attitudes toward risk can be incorporated into deliberations about climate policy; that is still a work in progress. It is, instead, to confirm that the first principles of risk-management approaches support the importance that negotiators place on each concept as they contemplate how to respond to nations’ obligations under Articles 2 and 4 of the United Nations Framework Convention on Climate Change – i.e., to frame actions that will help us avoid “dangerous anthropogenic interference with the climate system" while helping the most vulnerable among us to cope with the impacts of residual climate change.

6. Concluding Remarks

IPCC (2007c) tells us that insights derived from a risk-based perspective should now be inserted into public arguments over what to do about climate change – arguments that have heretofore too often been stuck in a false dichotomy between strained claims of certainty ("The verdict is in, now is the time for significant action regardless of cost, it won't cost much anyway, etc…"), and impassioned invocations that generic uncertainty justifies inaction ("Climate change is uncertain, we lack proof, mitigation is too expensive, R&D alone will solve the problem, etc…"). Sensible decisions and prudent management of risks require that we work in the "murky arena" between these two extremes by acknowledging that coping with uncertainty will play important roles in both the identification of policy objectives and the design of specific policy initiatives. People do not ignore uncertainty when making investments and purchasing insurance, nor should analysts and policy makers ignore uncertainty when assessing climate change policies.

The various sections of this paper can perhaps offer some preliminary guidance into how to find our way through the "murk". Section 2 tells us not to be too ambitious – to acknowledge that "mid-course corrections" will be required; and so it follows that greater attention has to be paid to exactly how to design a process by which these corrections can be accomplished. Section 3 tells us that the lens of risk-management can be productive in this regard; some macro-scale policies have already been framed in terms of hedging against particularly troubling possibilities, but there are no guarantees. Section 4 tells us not to expect that all outcomes can or should be quantified in units of currency; benefit-cost analyses may be the traditional standard for decision-analysis, but they must be complemented by risk-based approaches that can, when uncertainty dominates, carry the day as policies are designed. Section 5 adds the ambiguity of imbedding climate choices into discussions of sustainability that recognize attitudes toward inequality and risk. Every participant in the policy discussions must understand that his or her attitudes about both inequality (across time and space) and uncertainty are value-laden perspectives that have far-reaching consequences. Difficulties in creating and interpreting aggregate and disaggregated indices of risk surely persist, but adopting a risk perspective will bring new clarity to our understanding of the diversity and complexity of the climate problem. The strength of collections of direct or even qualitative profiles of risk lies in their ability to accommodate alternative metrics of vulnerability and/or reasons for concern in ways that allow comparisons across context.

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Appendix

Further discussion of existing damage estimates for climate change impacts in Figure 3, *areas II – V*.

Some investigators, notably West and Dowlatabadi (1999), Yohe et al. (1999), and Strzepek et al. (2001), have tried to capture the market-based implications of extreme events whose intensities and frequencies have or will be altered by a changing climate, but their efforts to add content to *area II* have been most successful when framed in the limiting context of impact thresholds beyond which climate variability produces severe damage.

Nordhaus and Boyer (2000) were essentially alone in their initial attempt to incorporate abrupt climate change into climate damage estimates; of course, Stern et al. (2006, 2007) as well as Nordhaus (2008) contributed to this small literature in attempts to expand our understanding of *area III.* It is important to note, however, that none of their approaches are anchored on robust analyses of economic damages that might be produced along abrupt climate change scenarios. They are, instead generally inferred from risk-premium calculations based on underlying utility structures and rather arbitrary assumptions. Nordhaus and Boyer (2000), for example, assigned low probabilities to large economic costs (on the order of 10 percent of global economic activity) for the middle of this century. These assumptions allowed them to report estimates of the willingness to pay to avoid such risk – estimates that are equivalent to the maximum amount that an individual would be willing to pay for "perfect insurance" that would eliminate (at a cost) all climate-related uncertainty about the future. Since no such insurance is available, though, these estimates should be viewed as indices of the economic cost of catastrophic climate change.

A few studies, authored for example by Nordhaus and Boyer (2000), Tol (2002a, 2002b), Stern et al. (2006, 2007), and Nordhaus (2006) among others, have tried to include some (but certainly not all) non-market impacts driven by trends in climate change (*area IV*). Their representations are not, however, particularly comprehensive since data are limited and estimation methods are sometimes extremely controversial.

The same authors tried to bring assessments of non-market impacts of extreme weather events into their integrated assessments of climate change; that is, they tried to work constructively in *area V.* Their efforts have, however, also been severely limited by a paucity of robust economic estimates of impacts. Link and Tol (2004) made some progress in this regard, but Stern et al. (2006) was the first attempt at comprehensive (though much criticized) inclusion to attract much attention. Finally, the Millennium Ecosystem Assessment (MEA, 2005) also contributed to *area IV* and *area V*, but that work stopped well short of trying to assign economic values to ecosystem services. Moreover, while various working groups within the MEA process developed scenarios within which those services produced utility, few of them paid much attention to climate change as a driver of risk.

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