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

Sponsored by

United States Environmental Protection Agency

U.S. Department of Energy

Executive Summary:

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

Modeling Climate Change Impacts and Associated Economic Damages

and

Research on Climate Change Impacts and Associated Economic Damages

June 2011

Workshop Sponsored by:

U.S. Environmental Protection Agency

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Workshop Report Prepared by:

ICF International

I. Introduction

In 2009 and early 2010, the U.S. Environmental Protection Agency (EPA) and U.S. Department of Energy (DOE) joined other U.S. government agencies in conducting an analysis of the social cost of carbon (SCC). The interagency working group used the DICE, FUND, and PAGE integrated assessment models (IAM) to estimate a range of values for the SCC from 2010 to 2050 for use in U.S. government regulatory impact analyses. The U.S. government analysis concluded in February 2010 and the estimated SCC values were first used in March 2010 in the analysis of DOE's Energy Conservation Standard for Small Electric Motors. In preparation for future revisions to the U.S. government SCC analysis, EPA and DOE seek to improve the understanding of the natural scientific and economic impacts of climate change. This enhanced understanding is also intended to inform ongoing work of the U.S. government to improve regulatory assessment and policy analysis related to climate change.

To further these objectives, the EPA National Center for Environmental Economics and Climate Change Division and the DOE Office of Climate Change Policy and Technology sponsored a pair of invitational workshops on November 18-19, 2010 and January 27-28, 2011. The November workshop focused on conceptual and methodological issues related to modeling and valuing climate change impacts. It also addressed the implications of these estimates for policy analysis. The January workshop reviewed recent research on physical impacts and associated economic damages for nine impact categories (e.g., human health, agriculture, sea level), with a particular focus on knowledge that might be used to improve IAMs.

This workshop summary was prepared by ICF International on behalf of EPA and DOE. It does not represent the official position or views of the U.S. government or its agencies, including EPA and DOE, nor has it been reviewed by the workshop speakers and other participants. The potential improvements and key findings outlined below represent the perspectives of one or more participants, as expressed at the workshops and summarized by the planning committee. However, these summaries do not necessarily represent consensus views, since none was sought at these workshops. This Executive Summary is organized into six sections: Physical Impacts Assessment; Valuation of Damages; Representing Impacts and Damages in Models; Communication of Estimates; Research and Collaboration; and Specific Impacts Sectors.

II. Physical Impacts Assessment

Participants made comments and suggestions related to impacts assessment, including the following:

- **More fully incorporate uncertainty**. Natural and social scientists should attempt to more fully characterize the uncertainty in impacts assessments, including parametric, stochastic, and structural uncertainty at all stages in the modeling process. Many of the current IAM inputs and parameters represent too narrow a range of possibilities. Complex and non-linear processes at the high ends of the impacts probability distribution (i.e., "fat tails") should be better characterized.

- **Consider both top-down and bottom-up approaches.** Estimates from both top-down and bottom-up approaches can help to estimate and bound the range of climate change impacts. For bottom-up approaches, the appropriate scale and detail may be different for each sector.

- **Incorporate threshold effects of physical and biological impacts.** Mechanistic and process models relying on basic principles (e.g., conservations of energy, plant biophysiology, ocean biogeochemistry) should be used, when possible, to extrapolate responses to new conditions, since statistical methods may not capture non-linear threshold effects of unprecedented levels of change. When climate change impacts are expected to be within or close to the range of past variations, statistical models are appropriate.

- **Capture climate variables beyond global mean temperature.** A better characterization of multiple climate variables (e.g., precipitation, storms, seasonal and diurnal temperature variations, rate of temperature change) and threshold effects on a geographically disaggregated scale could improve model calibration and the accuracy of local damage projections.

- **Focus research efforts on sectors that could have the largest influence on overall damage estimates.** This will include research on impact categories that could comprise a large share of total damages but where relatively little information has been collected to date. Researchers should not simply focus on issues that are easiest to approach. Research priorities should be guided by the combination of potential consequences and uncertainty, not one or the other alone.

- **Increase focus on high-impact events, multi-century impacts.** Existing studies tend to examine the means of the impacts probability distribution, neglecting the low-probability, high impact tails of the distribution, which can have a significant influence on IAM results. Impact studies should address this gap, recognize the potential for unexpected and unpredictable events, and attempt to model very long-term impacts (e.g., beyond 2100), despite great associated uncertainty. To do this, modelers should develop more complete multi-century projections for socio-economic and climate inputs including estimates of socio-economic uncertainty.

- **Rigorously test, compare, and evaluate impact models**. Model intercomparison projects have helped to improve physical climate models and could be used to improve impact models.

III. Valuation of Damages

Comments and suggestions related to damage valuation included the following:

- **Consider alternate functional forms for damage functions.** Representation of damages could be improved by: evaluating the additive or multiplicative nature of impacts; better incorporating discontinuities; better capturing natural capital and its interactions with physical and social capital; and generally considering a broader set of functional forms. Alternate forms are particularly important given the challenges in extrapolating damage functions calibrated at 2-3°C warming to considerably higher global mean temperature increases.

- **Clearly incorporate human behavioral responses.** Adaptation and technological development should be more fully incorporated in estimates of climate change impacts, and the underlying assumptions associated with those factors should be clearly articulated.

- **Consider different ways of equity weighting when conducting social welfare analysis of climate policies.** Several workshop participants suggested considering different ways of incorporating equity weights into the SCC or IAMs more generally. For example, most IAMs use a utility function with a single parameter that controls preferences regarding intra-generational equity, inter-generational equity, and risk aversion. Future research should explore alternative functional forms that allow these effects to be disentangled.

- **Fully account for non-market impacts and non-use values.** This includes improving estimates of impacts currently included in some models (e.g., health impacts) and incorporating impacts currently missing from most models (e.g., ocean acidification, loss of cultural heritage). Revealed and stated preference estimates and benefit-transfer methods should be improved and estimated jointly to mitigate problems with each.

- **Consider "outer measures" of climate damages.** Developing a model for a highly simplified but inclusive "outer" measure of climate change damages may help provide an upper bound on SCC estimates. Current bottom-up models are "inner" measures that attempt to capture and sum the individual components of climate damages. Since it is challenging to capture all of the components and interactions between them, these models will tend toward underestimation.

IV. Representing Impacts and Damages in Models

Throughout both workshops, but especially during the first, participants made suggestions related to integrating impacts and damages in models. These comments included the following:

- **Improve both aggregated and disaggregated models while utilizing the strengths of each.** There are important roles for models across the spectrum of aggregation, as more or less aggregation may be appropriate for different applications. Model type and analysis time scale should be matched to analytical objective. Since aggregation can contribute to a bias in impact estimates, some models should be less aggregated spatially, temporally, and sectorally to more realistically represent impact mechanisms. Since disaggregated models can incorporate more realistic impact mechanisms and use empirical data to estimate model parameters, they can be used to calibrate components of more comprehensive aggregated models.

- **Incorporate more sectors.** IAMs should include a broader range of sectors. For example, no IAMs currently represent ocean acidification.

- **Incorporate interactions between sectors.** Interactions between sectors (and among climate and non-climate stressors) may be synergistic or antagonistic, additive, multiplicative, or subtractive, making cumulative impacts larger or smaller than the sum of the individual impacts. Double-counting should be avoided.

- **Use consistent scenarios.** Consistent socio-economic and climate scenarios should be used in impact and damage assessment to facilitate inter-comparison, integration, and combination of estimates.

- **Increase model flexibility to facilitate improvements.** IAMs should be (re)designed to facilitate updates to models or model components as new research develops. A more flexible or modular structure would allow components to be individually updated or replaced.

- **Conduct new empirical studies and better incorporate existing research.** IAMs need new primary impacts research from which to draw. Research needs include empirical studies on: physical impacts, monetization of damages, decision making under uncertainty, adaptation-related technological change, adaptive capacity, tipping points, and impacts beyond 2100. IAMs could also be improved by drawing more on the existing body of research.

V. Identify metrics for model validation. Metrics and methods of validation are needed to assess models and model results. Communication of Estimates

Participants, particularly at the first workshop, made comments and suggestions related to the communication of impacts and damages estimates. These comments included the following:

- **Increase transparency.** IAMs should be made more accessible and transparent, including their key assumptions, structural equations, parameter values, and underlying empirical studies.

- **Fully and clearly communicate uncertainty.** Communication should help decision makers and the public fully and clearly understand uncertainty and its implications. The full range of model outputs should be communicated and used, rather than focusing on one central value from a set of model runs.

- **Consider other metrics.** Multiple criteria, in addition to the SCC and cost-benefit analysis, should be used for climate-related regulatory analysis, including additional cost-effectiveness measures.

VI. Research and Collaboration

Comments and suggestions related to research and collaboration included the following:

- **Increase collaboration and communication between natural scientists, economists, and modelers.** Collaboration and communication should be increased between all parties involved in impacts assessment, damages valuation, and integrated assessment modeling. Impacts assessment and valuation efforts should be coordinated with existing efforts such as the National Climate Assessment and international impacts and valuation efforts. IAM data sources, damage functions, and outputs should be reviewed by relevant members of the Impacts, Adaptation, and Vulnerability (IAV) and economic valuation communities to ensure that IAMs reflect the current state of the primary literature for each of the impact categories.

- **Increase capacity to address challenges.** Additional funding and staff are needed to help address existing impacts and damages assessment challenges.

VII. Specific Impacts Sectors

The second workshop focused on the current state of research in nine impact categories. This section highlights key research findings and recommendations for future research for each of the categories.

Storms and Other Extreme Weather Events

- Fewer tropical storms are expected in the future, but average wind speeds and precipitation totals are expected to increase. The intensity of the strongest storms is expected to increase.

- Estimates in the literature for increases in cyclone property damages due to climate change range from 0.002 to 0.006% of global GDP. Increases in property damages from all extreme events (including cyclones) due to climate change under an A1B scenario, according to one study, range from $47-$100 billion (2008 dollars) per year, or 0.008-0.018% of GDP, by 2100.

- Fatalities may increase or decrease due to climate change impacts on extreme events, as deaths from tropical cyclones may decrease more than deaths from other extreme events (e.g., heat waves) increase. Tropical cyclones are expected to continue to be the dominant cause of extreme event-related damages.

Water Resources

- Water demand, supply, and management should be modeled on a river basin scale to effectively estimate climate change impacts.

- National estimates from the literature of climate change damages to water resources range from $12-$60 billion (2009 dollars) per year for the United States according to analyses in a range of studies.

- Coupling approaches that model changes using regional hydrologic models and those using regional economic models could help bridge some gaps in water resources damage estimation.

Human Health

- The majority of climate change health effects result from diarrhea, malnutrition, and malaria. The World Health Organization estimates that the costs to treat climate change-related cases of diarrhea, malnutrition, and malaria in 2030 would be $4 to $13 billion under a scenario in which CO_2 is stabilized at 750ppm by 2210. The study predicts a 3%, 10%, and 5% increase in cases of diarrhea, malnutrition, and malaria, respectively.

- Health impact valuation depends largely on mortality valuation, particularly in developing countries and particularly among children. Adjusting the value of a statistical life for income is critical for accurate valuation.

Agriculture

- Estimates in the literature project the global range of yield changes in the 2050s to be approximately -30 to +20% under a 2.3°C mean global temperature increase (relative to 1961-1990).

- Average global effects of climate change on agriculture are expected to be positive in the short term and negative in the long term. The location of the inflection points is unknown.

    - CO_2 fertilization from increasing CO_2 concentrations will benefit some plants (C_3 plants) more than others (C_4 plants). Elevated CO_2 concentrations especially benefit weeds.

- Agriculture contributes only 2-3% of U.S. GDP, but the highly inelastic nature of agricultural demand means that even a small reduction in agricultural production from climate change could result in large price changes and large welfare losses.

- Adaptation and technological change can help to mitigate the impacts of climate change on agriculture. A key challenge will be producing heat and drought tolerant plants with high yields.

Sea Level Rise

- Climate-induced sea level rise will be compounded by both natural and human-induced subsidence in many densely-populated coastal areas.

- Emissions abatement may stabilize the rate and ultimate total amount (in 100s of years) of sea level rise, but not reduce the current significant commitment to sea level rise.

- The valuation of sea level rise damages depends heavily on wetland values and adaptation.

Marine Ecosystems and Resources

- Increasing atmospheric CO_2 concentrations cause ocean CO_2 concentrations to increase, decreasing ocean pH, and decreasing saturation states for calcite and aragonite, which are used by marine animals to produce calcareous parts (e.g., shells).

- Damages from decreased mollusk harvest revenues due to a 0.1-0.2 ocean pH decrease are estimated at $1.7 to $10 billion in net present (2007) value losses through 2060. Under the A1FI scenario pH decreases of 0.1 and 0.2 are expected by approximately 2040 and 2060, respectively.

- Assessments using bio-climate envelopes, minimum realistic models, and ecosystem and food web models would be beneficial to estimate marine impacts.

- A wide variety of studies to estimate damages is needed, using both revealed and stated preferences, to estimate total economic value of marine ecosystems and resources. Analyzing the results available from multiple existing studies could be used in a benefit transfer study to estimate economic value by transferring available information into the appropriate context.

Terrestrial Ecosystems and Forestry

- Three major types of terrestrial ecosystem impacts are expected: changes in vegetation distribution and dynamics, wildfire dynamics, and species extinction risks. For example, predicted global vertebrate extinctions due to land use and climate change range from over 30% to nearly 60% for >2 degree warming.

- Understanding changes in pest outbreaks, interior wetlands, and snow pack are important gaps.

- Natural scientists and economists need to work together to identify biophysical impacts assessment endpoints best suited for use in revealed and stated preference valuation studies.

Energy Production and Consumption

- Energy impacts may be beneficial for small to modest climate change, due primarily to decreases in heating requirements for buildings, but are expected to be dominated by negative impacts in the long-run and at higher levels of temperature change.

- More data and research are needed to evaluate the effects from wildfire and sea level rise on power sector infrastructure, and temperature impacts on electricity production, transmission, and distribution.

Socio-economic and Geopolitical Impacts

- Climate change-induced natural disasters, migration caused by sea level rise and other climate factors, and increasing resource scarcity may promote conflict; however, the policy debate regarding socio-economic and geopolitical impacts from climate change is well ahead of its academic foundation, and sometimes even contrary to the best evidence.

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

Sponsored by United States Environmental Protection Agency, U.S. Department of Energy

November 18-19, 2010 Omni Shoreham Hotel, Washington, DC

Workshop Report:

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

Modeling Climate Change Impacts and Associated Economic Damages

January 2011

Workshop Sponsored by:

U.S. Environmental Protection Agency

U.S. Department of Energy

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ICF International

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I. Introduction

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

This report is organized as follows:

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

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

Context

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

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

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

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

Workshop Format

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

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

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

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

II. Potential Future Improvements Suggested by Workshop Participants

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

The section is organized into four categories of comments:

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

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

Overarching comments

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

- **Improve both aggregated and disaggregated models while highlighting the strengths of each.** There was considerable debate about the appropriate level of disaggregation and the merits of using more or less aggregated models for different types of applications. Several participants suggested that increased attention to disaggregation was important to understanding the true impacts associated with climate change. However, some were skeptical of current capabilities to downscale global climate models (GCMs) to produce reliable disaggregated estimates of impacts, at local or regional scales. In the end many participants suggested that a two-track approach is necessary and that there are important roles for models across the spectrum of aggregation.
    - ***Build better disaggregated models.*** Many conference participants recommended using more disaggregated models, emphasizing that aggregation can contribute to a bias in impact estimates. (For example, if damages increase at an increasing rate with higher local temperatures, then using regionally averaged temperature increases would underestimate the average local damages.) They recommended that models increase disaggregation spatially and sectorally to allow for more realistic representations of impact mechanisms. They also emphasized the need to explicitly model the temporal and spatial variability of climate impacts.
    - ***Better inform calibration of aggregated models with disaggregated models.*** Some participants suggested using more disaggregated models to help inform calibration of more aggregated models. Several noted it is possible to incorporate more realistic impact mechanisms in disaggregated models, and to more accurately parameterize such models using empirical data. Participants suggested that the predictions of more disaggregated models might be useful to calibrate components of the more general and comprehensive aggregated models (at least within the range of temperature changes observed in the data).
- **Increase model flexibility to facilitate improvements.** Several participants suggested that IAMs should be (re)designed to be more flexible so that it is easier to update the models or model components to incorporate new research findings. At least two participants suggested moving to a more modular structure where different components could easily be updated or replaced by newer modules as research develops. For example, increased modularity could allow researchers to replace sector-specific damage functions when new research points to different parameter values or functional forms. While IAMs, which link climate models to impact and economic models, are somewhat modular in theory, this has not always been the case in practice. Modularity could be introduced in model implementation in multiple ways. A simple

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

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

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

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

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

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

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

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

Comments related to the modeling of natural systems in IAMs

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

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

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

Comments related to the modeling of human systems in IAMs

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

- **Consider alternative functional forms for damage functions.** Numerous conference participants highlighted the need to re-evaluate the functional form of the models’ damage representations. The suggested improvements included: evaluating whether impacts should be additive or multiplicative[3]; better incorporating discontinuities; making damage functions more reactive to extreme temperature increases; and generally considering a broader set of functional forms for damage functions. It is important to consider alternative functional forms given the challenges in extrapolating damage functions calibrated at 2-3 °C global warming to considerably higher global average temperature increases.

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

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

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

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

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

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

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

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

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

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

Comments related to the communication of IAM results

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

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

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

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

- **Consider other metrics.** Many participants questioned the usefulness and effectiveness of the SCC as a single criterion for regulatory analysis. Several participants discussed the potential shortcomings of cost-benefit analysis in a climate change context. Some participants indicated that the SCC may be one relevant measure, but they encouraged the use of multiple criteria for regulatory analysis, in addition to the SCC. Participants suggested using additional measures to assess cost-effectiveness, such as using the shadow price of a range of policy targets as a reference.

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

III. Chronological Presentation of Workshop Proceedings

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

Workshop Introduction

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

Opening Remarks

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

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

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

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

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

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

Progress Toward a Social Cost of Carbon

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

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

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

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

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

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

Session 1: Overview of Existing Integrated Assessment Models

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

Overview of Integrated Assessment Models

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

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

DICE

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

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

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

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

PAGE

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

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

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

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

FUND

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

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

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

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

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

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

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

GCAM and Development of iESM

Next, Dr. Leon Clarke presented the climate impacts representation in GCAM, which is an example of one of the higher resolution IAMs described by Dr. Edmonds. Dr. Clarke explained that GCAM is a dynamic-recursive model that includes a climate model based on MAGICC and the energy-economy model developed by Dr. Edmonds and Dr. Reilly. While the model's basic inputs are similar to the more aggregate models, GCAM includes a much higher level of detail for each sector. For example, GCAM includes detail related to energy system resources, technology assumptions, demand technologies, and agricultural productivity. Dr. Clarke noted that GCAM is particularly useful for examining impacts that involve interactions among the various systems represented in IAMs. However, he also noted that aggregating and monetizing all impacts is not a core objective of GCAM or similar, higher-resolutions IAMs.

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

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

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

IGSM

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

Dr. Reilly then discussed the characterization of uncertainty in the IGSM. Uncertainty in the model arises from: emissions uncertainties (due to uncertain socio-economic inputs); climate system response uncertainties; and greenhouse gas cycle uncertainties. Dr. Reilly discussed the impacts of different stabilization targets, including the likelihood of different levels of temperature increase under each policy. He showed probability distribution functions for five different policy scenarios. He presented an uncertainty analysis that showed that the five cases used in the interagency process are conservative estimates of CO_2 concentration projections and do not capture the full range of IGSM estimates. Dr. Reilly also compared the IGSM scenarios to the IPCC SRES scenarios for global mean temperature change. Again, the IPCC results show a low bias and do not cover the full range of IGSM estimates. Dr. Reilly concluded that the higher impacts estimated by IGSM as compared to IPCC indicates that looking at the issues in an integrated way can produce different answers than looking at the issues individually.

Session 1 Discussion

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

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

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

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

Another participant discussed the vast uncertainty and guesswork involved in the IAMs and SCC estimates. He questioned how best to proceed given the unprecedented uncertainty around the SCC estimates. He proposed several options, including: forging ahead and producing a number; admitting the uncertainty is too great and avoiding the exercise altogether; or some hybrid. He further questioned the applicability of cost-benefit analysis for climate policy decisions. Dr. Hope argued that despite the uncertainty, it is still beneficial to estimate the SCC. However, it is crucial to always present a range of values and an explanation of what is and is not included in the estimate, as well as an explanation of what information is needed to narrow the range.

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

Session 2: Near-Term DOE and EPA Efforts

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

Proposed Impacts Knowledge Platform

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

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

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

Proposed Generalized Modeling Framework

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

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

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

Session 2 Discussion

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

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

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

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

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

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

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

Session 3, Part 1

Session 3 was split into two parts occurring in the afternoon of Day 1 and the morning of Day 2. The first part of Session 3 was moderated by Ann Wolverton of the U.S. Environmental Protection Agency and included two presentations by Ian Sue Wing, Boston University, one as a replacement for Karen Fisher-Vanden, Pennsylvania State University, as well as a presentation by Brian O’Neill, National Center for Atmospheric Research. The session began to explore critical modeling issues in assessment and valuation of climate change impacts, including: sectoral and regional disaggregation and interactions, adaptation and technological change, and multi-century scenario development and socio-economic uncertainty.

Sectoral and Regional Disaggregation and Interactions

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

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

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

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

During the question and answer session, one participant challenged the notion that intertemporal valuation is done well and asked how ecosystem services are represented. Dr. Sue Wing suggested ecosystem services be valued using a Ramsey framework specified with ecosystem service constraints. The participant commended the answer on how to incorporate ecosystem services but noted there is generally little knowledge about the welfare derived from non-monetized services, such as ecosystem services in a climate change context. Dr. Sue Wing acknowledged the current lack of knowledge but indicated there are ways to make progress. Another participant asked about climate impacts damages and the regional and local specificity from the perspective of infrastructure risk. Dr. Sue Wing explained that climate damages can be set to change capital accumulation by reducing investment rates or directly destroying capital stocks. However, he noted the difficulty associated with projecting specificity into the future.

Adaptation and Technological Change

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

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

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

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

Multi-century Scenario Development and Socio-Economic Uncertainty

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

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

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

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

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

Session 3, Part 1 Discussion

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

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

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

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

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

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

Session 3, Part 2

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

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

Incorporation of Climate System Uncertainty into IAMs

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

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

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

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

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

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

Extrapolation of Damage Estimates to High Temperatures: Damage Function Shapes

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

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

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

During the question and answer session, one participant seconded the call for backstop research that will help to promote the ability to undertake mid-course corrections. Dr. Weitzman supported this, arguing that climate change has the probability of being the worst fat-tailed issue. Another participant noted that even if the climate trajectory follows the mid to low IPCC projections, the consequences could be disastrous. He argued that geoengineering is the biggest fat tail problem, with the possibility of disaster outcomes. He suggested focusing the discussion more on known problems and less on speculative issues. A third participant noted the huge potential health effects of geoengineering solutions.

Earth System Tipping Points

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

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

Dr. Lenton then indicated that according to the expert elicitation, there is a 16 percent probability that one of five tipping points will be passed under 2-4°C warming and a 56 percent probability that one of five tipping points will be passed under 4°C warming. He explained that there may also be interactions between tipping points including both positive and negative feedbacks. For example, a weakening of the Atlantic thermohaline circulation could end up disrupting the seasonal onset of the West African Monsoon, which in one model could lead to a greening of the region, a rare positive impact. The strengthening of the Indian summer monsoon is a possible tipping point that is perhaps more sensitive to aerosols than to temperature changes. GHG impacts on this tipping element are likely being offset by the already occurring brown haze in the region. Finally, Dr. Lenton included several prospects for early warning signals, which could help societies manage the risk posed by tipping points. These include slowing down of a climate system (e.g., lower frequency of oscillation), increasing variability, and skewness of response.

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

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

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

Potential Economic Catastrophes

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

Dr. Toman then presented the standard rational choice approaches and the challenges with applying them to value global climate catastrophes. He noted the limited information on possible states of the world, the fat tails of the distribution, and, particularly, the indication from behavioral economics of systematic assessment errors by the general public. He argued that decision makers need to exercise their judgment as agents of the general public in evaluations.

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

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

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

Nonmarket Impacts

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

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

Dr. Hanemann concluded that there is a great need to downscale and disaggregate models. He suggested a modular approach incorporating a network of models. He argued that damage functions are too simple in current models. Dr. Hanemann suggested that climate change impacts be reframed in terms of risk, with greater emphasis on downside risk-adjusted impact. He also noted the need to treat consumption as an imperfect substitute for the environment.

Session 3, Part 2 Discussion

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

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

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

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

Another topic discussed during this session was the role of the SCC and other valuation methods. One participant distinguished between the need to outline a research agenda to characterize and monetize impacts and the need to improve the necessarily crude and narrow exercise to develop an SCC number for OMB guidance. Another participant emphasized the need to articulate regional impacts and to engage the public, regardless of whether regional impacts are summed to a single number. A third participant suggested that the economic impacts work, and specifically the SCC, be updated to reflect the urgency and seriousness of climate change described by natural scientists. Lastly, a participant underscored the regulatory importance of the SCC as the communication message to the world. As such, she suggested two short-term improvements to the SCC: to tie down the high end of damages and to make the discount rate endogenous to growth. Another participant noted this is not as straightforward as the commenter makes it sound.

Session 4: Implications for Climate Policy Analysis and Design

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

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

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

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

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

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

Dr. Kopp outlined the information likely to be of future value to legislation and foreign policy. This information includes detail on the distribution and severity of damages; characterization of adaptation potential to lower damages; and estimates of damage sensitivity to the speed of climate change. Finally, Dr. Kopp highlighted the missing element in current SCC analysis: the complete lack of non-use values, bequest values, existence values, and passive use values. He noted that these methods of non-market valuation are those classically used in intra- and inter-generational valuation.

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

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

Implications for Addressing Equity and Natural Capital Impacts

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

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

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

During the question and answer session, one participant suggested moving away from the Ramsey equation, as it builds in aggregation. Dr. Heal agreed, noting that the Ramsey equation promotes thinking as a representative individual and therefore neglects equity. He explained that the use of distributional rates is returning after having fallen out of use.

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

Implications for Choice of Policy Targets for Cost-Effectiveness Analysis

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

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

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

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

During the question and answer session, Dr. Keohane noted that the SCC would be approximately three times larger if the goal was stabilization. One participant suggested that cumulative emissions would be a more appropriate metric than emissions concentration. Another participant commended the topic of the presentation, underlining the importance of cost-effectiveness questions. He suggested that there are more effective communication tools, such as illustrating how New York will begin to look like DC, and DC like Florida under the effects of climate change.

Implications for Managing Climate Risks

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

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

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

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

Session 4 Discussion

Following the questions on Dr. Cooke's presentation, the discussion portion of Session 4 began. One participant pointed out that the interagency process did produce a range of estimates and questioned why the focus has been on the central estimate rather than the full range. The panel concurred, emphasizing the need to communicate the full range. Dr. Heal suggested the interagency-produced range provides a lower bound to a much wider and higher range. Another participant emphasized a focus on targets with SCC estimates developed to produce that target. For example, the participant cited a study that concluded a $75-$100 shadow price would be needed to reduce emissions by 17 percent by 2020. However, a member of the panel emphasized that this may not be possible, given that there is no nationally agreed-upon emissions goal in the United States against which policies can be evaluated. Until that happens, analysts must use the tools available to them to evaluate the impacts of regulations, one of which is benefit-cost analysis.

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

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

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

Session 5: Workshop Wrap-up

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

Next, Dr. Duke emphasized that this workshop demonstrates DOE's and Secretary Chu's commitment to integrity in science, economics, and policy. Keeping in that theme, Dr. Duke acknowledged that the models used by the interagency process use reduced-form damage functions with simple functional forms. He said that he looked forward to improving them over time. He also noted that DOE is funding work with the higher resolution models, such as GCAM and IGSM. He highlighted the radically different nature of these models, remarking that perhaps we have been "looking for the keys under one streetlight" and instead, "need to build more streetlights." Dr. Duke echoed Dr. Cooke's proposal to optimize risk under constraint and Dr. Heal's notion of the deeply imperfect substitutability of natural capital.

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

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

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

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

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

Sponsored by United States Environmental Protection Agency

U.S. Department of Energy

November 18-19, 2010 Omni Shoreham Hotel, Washington, DC

APPENDIX

to the

DRAFT Workshop Report:

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

Modeling Climate Change Impacts and Associated Economic Damages

January 2011

Workshop Sponsored by:

U.S. Environmental Protection Agency

U.S. Department of Energy

Workshop Report Prepared by:

ICF International

Appendix Contents

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

Sponsored by EPA United States Environmental Protection Agency; U.S. Department of Energy

November 18-19, 2010 Omni Shoreham Hotel, Washington, DC

Workshop Agenda with Charge Questions

MODELING CLIMATE CHANGE IMPACTS AND ASSOCIATED ECONOMIC DAMAGES

Charge Questions: The following charge questions (appearing in boxes) were given to each of the workshop speakers. Each speaker was asked to write a short abstract (approximately 3-5 pages) and organize their presentations around these questions, though they also were encouraged to think more broadly and to consider other ideas as they see fit. The purpose of the papers and presentations was to briefly summarize the current state of the art in each area and to set the scene for a productive discussion at the workshop, not necessarily to provide complete answers to all charge questions.

November 18, 2010

Workshop Introduction

8:30 – 8:35 ***Welcome and Introductions***
Elizabeth Kopits, U.S. Environmental Protection Agency

8:35 – 9:00 ***Opening Remarks***
Bob Perciasepe, Deputy Administrator, U.S. Environmental Protection Agency
Steve Koonin, Under Secretary for Science, U.S. Department of Energy

9:00 – 9:25 ***Progress Toward a Social Cost of Carbon***
Michael Greenstone, Massachusetts Institute of Technology

Session 1: Overview of Existing Integrated Assessment Models

Moderator: Stephanie Waldhoff, U.S. Environmental Protection Agency

Charge: Describe
(1) the history of climate-economic integrated assessment modeling,
(2) the major reduced-form and higher-complexity IAMs currently in use,
(3) the main strengths and weaknesses of each model,
(4) current areas of active research, and
(5) how these areas of active research might inform policy and regulatory analysis.

9:25 – 9:50 ***Overview of Integrated Assessment Models***
Jae Edmonds, Pacific Northwest National Laboratory

Models Used for the Development of Current USG SCC Values

Charge for all model presenters: Describe the current state of your model and any recent, planned, or potential modifications. Specifically:

(1) Describe the basic structure of your model. What are key exogenous and endogenous variables?
(2) Discuss the physical impacts included in your model and how the corresponding market and non-market economic damages are calculated. What major impacts and damage categories are not included (e.g., ocean acidification and associated damages)? To what extent does the model incorporate the physical cycles for non-CO2 GHGs?
(3) What assumptions does your model make about adaptation?
(4) What assumptions does your model make about climate system "tipping points," catastrophic impacts and the corresponding economic damages?
(5) How does your model incorporate uncertainty in physical parameters such as climate sensitivity and economic parameters such as the discount rate?

9:50–10:15 ***DICE***
Steve Newbold, U.S. Environmental Protection Agency

10:15–10:40 ***PAGE***
Christopher Hope, University of Cambridge

10:40–10:55 ***Break***

10:55–11:20 ***FUND***
David Anthoff, University of California, Berkeley

Representation of Climate Impacts in other Integrated Assessment Models

Charge for all model presenters: Describe the current state of your model and any recent, planned, or potential modifications. Specifically:

(1) Describe the basic structure of your model. What are key exogenous and endogenous variables?
(2) Discuss the physical impacts included in your model and how the corresponding market and non-market economic damages are calculated. What major impacts and damage categories are not included (e.g., ocean acidification and associated damages)? To what extent does the model incorporate the physical cycles for non-CO2 GHGs?
(3) What assumptions does your model make about adaptation?
(4) What assumptions does your model make about climate system "tipping points," catastrophic impacts and the corresponding economic damages?
(5) How does your model incorporate uncertainty in physical parameters such as climate sensitivity and economic parameters such as the discount rate?

11:20–11:45 ***GCAM*** (JGCRI – UMD/PNNL) ***and Development of iESM*** (PNNL/LBNL/ORNL)
Leon Clarke, Pacific Northwest National Laboratory

11:45–12:10 ***IGSM*** (MIT)
John Reilly, Massachusetts Institute of Technology

12:10–12:40 **Discussion**

12:40 – 1:40 ***Lunch***

Session 2: Near-Term DOE and EPA Efforts

Moderator: Ann Wolverton, U.S. Environmental Protection Agency

1:40 – 2:00 ***Proposed Impacts Knowledge Platform***
Bob Kopp, U.S. Department of Energy
Nisha Krishnan, Resources for the Future

2:00 – 2:20 ***Proposed Generalized Modeling Framework***
Alex Marten, U.S. Environmental Protection Agency

2:20 – 2:40 **Discussion**

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

Moderator: Ann Wolverton, U.S. Environmental Protection Agency

2:40 – 3:10 ***Sectoral and Regional Disaggregation and Interactions***
Ian Sue Wing, Boston University

Charge: Review the sectoral and regional representation of economic damages in integrated assessment models. Specifically, discuss:

(1) how damages in one category and one region may affect other categories and regions,
(2) the relative magnitude/importance of these interactions,
(3) how these relationships might be represented in an IAM, and
(4) gaps in the way existing IAMs represent these relationships and major challenges in improving these representations.

3:10–3:20 ***Break***

3:20–3:50 ***Adaptation and Technological Change***
Ian Sue Wing, Boston University on behalf of Karen Fisher-Vanden, Pennsylvania State University

Charge: Drawing from the recent literature, discuss how adaptation may influence the net social costs of climate change (adaptation costs plus residual climate damages). Specifically, discuss:

(1) relevant studies on the observed or potential effectiveness of adaptive measures, and on private behaviors and public projects regarding adaptation;
(2) relevant studies on how to forecast adaptive capacity;
(3) how adaptation and technical change could be represented in an IAM (for at least one illustrative sector);
(4) whether the information required to calibrate such a model is currently available, and, if not, what new research is needed; and
(5) how well or poorly existing IAMs incorporate the existing body of evidence on adaptation.

3:50–4:20 ***Multi-century Scenario Development and Socio-Economic Uncertainty***
Brian O'Neill, National Center for Atmospheric Research

Charge: Discuss the methods and difficulties associated with forecasting a baseline scenario for greenhouse gas emissions and socio-economic variables (e.g., population and GDP), including the particular challenges in extending these scenarios for multiple centuries. Specifically, discuss:

(1) relevant studies on long-term demographic and economic scenarios and the assumptions used to develop these scenarios;
(2) relevant studies on the evolution of energy systems and the assumptions used to develop these scenarios;
(3) the range of plausible future scenarios extending to at least 2300, including the range incorporated into major IAMs; and
(4) what are the main challenges in representing such multi-century forecasts in an IAM.

4:20–5:00 **Discussion**

November 19, 2010

Day 2 Introduction

8:30–8:40 ***Welcome; Recap of Day 1; Overview of Day 2***
Elizabeth Kopits, U.S. Environmental Protection Agency

Session 3B: Critical Modeling Issues in Assessment and Valuation of Climate Change Impacts (cont.)

Moderator: Bob Kopp, U.S. Department of Energy

8:40–9:10 ***Incorporation of Climate System Uncertainty into IAMs***
Gerard Roe, University of Washington

Charge: Discuss:
(1) the major sources of climate system uncertainty that could be represented in reduced-form integrated assessment models (such as DICE, PAGE, and FUND),
(2) the difficulties/issues with representing the uncertainty surrounding these parameters in IAMs, and
(3) relevant studies that estimate probability density functions for these parameters.

9:10–9:40 ***Extrapolation of Damage Estimates to High Temperatures: Damage Function Shapes***
Marty Weitzman, Harvard University

Charge: Discuss:
(1) how damage functions behave at high temperatures in the principal reduced-form IAMs, including DICE, PAGE, and FUND;
(2) the reasoning underlying the selection of these functional forms and alternative formulations that have been proposed in the literature;
(3) the relative strengths of these various functional forms in terms of extrapolating damage estimates to high temperatures; and
(4) the difficulties/issues with incorporating uncertainty regarding such "out of sample forecasts."

9:40–10:10 ***Earth System Tipping Points***
Tim Lenton, University of East Anglia

Charge: Discuss:
(1) evidence on potential Earth system tipping points, including the most recent estimates of these tipping points based on modeling studies, paleoclimatic data, expert elicitation, and other relevant sources; and
(2) available estimates of their probabilities under different scenarios.

10:10–10:30 ***Break***

10:30–11:00 ***Potential Economic Catastrophes***
Michael Toman, World Bank

Charge: Discuss:
(1) the literature on the potential economic damages associated with catastrophic climate impacts, potentially related to Earth system tipping points;
(2) how these damages might be incorporated into reduced-form and/or higher-complexity IAMs; and
(3) the key challenges associated with translating information on the likelihood and physical consequences of particular tipping points into economic damages.

11:00–11:30 ***Nonmarket Impacts***
Michael Hanemann, University of California, Berkeley

Charge: Discuss:
(1) recent studies of potential non-market impacts of climate change;
(2) how the value of such impacts are currently represented in IAMs;
(3) how such non-market impacts could be better represented in IAMs, possibly including but not necessarily limited to alternative damage functional forms and multivariate utility functions; and
(4) key challenges of quantifying and incorporating non-market impacts into IAMs.

11:30–12:30 **Discussion**

12:30–1:30 ***Lunch***

Session 4: Implications for Climate Policy Analysis and Design
Moderator: Charles Griffiths, U.S. Environmental Protection Agency

1:30–2:00 ***Implications for Design and Benefit-Cost Analysis of Emission Reduction Policies***
Ray Kopp, Resources for the Future

Charge: How can improved IAMs, as discussed in Sessions 1-3, aid in the design and evaluation of domestic emission reduction policies such as cap-and-trade or carbon taxes, and inform negotiations of international climate agreements?

2:00–2:30 ***Implications for Addressing Equity and Natural Capital Impacts***

Geoff Heal, Columbia University

Charge: How can improved IAMs, as discussed in Sessions 1-3, help policy analysts address intra-generational equity concerns, account for impacts on natural capital and ecosystem services, and better represent the substitutability between ecosystem services and market goods?

2:30–3:00 ***Implications for Choice of Policy Targets for Cost-Effectiveness Analysis***
Nat Keohane, Environmental Defense Fund

Charge: How can improved IAMs, as discussed in Sessions 1-3, help inform a cost-effectiveness analysis of various policy actions that reduce CO2 emissions? For example, how could these models help in choosing a temperature or carbon concentration target for national policies or international agreements? Are there other environmental endpoints that should be considered in cost-effectiveness analysis of climate policies (e.g., targets associated with ocean acidification)?

3:00–3:10 ***Break***

3:10–3:40 ***Implications for Managing Climate Risks***
Roger Cooke, Resources for the Future

Charge: How could improved IAMs, along the lines discussed in Sessions 1-3, help inform a risk management analysis of various policy actions that reduce CO2 emissions? For example, how could these models aid in the design of adaptation policies to manage increased climate and weather related risks, such as increased flood frequencies and storm damages?

3:40–4:15 **Discussion**

Session 5: Workshop Wrap-up

4:15–4:30 ***Summary Comments by U.S. Department of Energy***
Rick Duke, Deputy Assistant Secretary for Climate Policy

4:30–4:45 ***Summary Comments by U.S. Environmental Protection Agency***
Al McGartland, Director of the National Center for Environmental Economics

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Extended Abstracts

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Estimating the Social Cost of Carbon for the United States Government

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The climate is a key ingredient in the earth's complex system that sustains human life and well being. According to the United Nation's Intergovernmental Panel on Climate Change (IPCC), the emissions of greenhouse gases (GHG) due to human activity, large the combustion of fossil fuels like coal, is "very likely" altering the earth's climate, most notably by increasing temperatures, precipitation levels and weather variability. Without coordinated policy around the globe, state of the art climate models predict that the mean temperature in the United States will increase by about 10.7° F by the end of the century (Deschenes and Greenstone 2010). Further, the distribution of daily temperatures is projected to increase in ways that pose serious challenges to well being; for example, the number of days per year where the typical American will experience a mean (average of the minimum and maximum) temperature that exceeds 90° F is projected to increase from the current 1.3 days to a 32.2 days (ibid). The especially troubling statistic is that the hottest days pose the greatest threat to human well being.

It appeared that the United States and possibly the major emitters were poised to come together to confront climate change by adopting a coordinated set of policies that could have included linked cap and trade systems. However, the failure of the United States Government to institute such a system and the non-binding commitments from the Copenhagen Accord seem to have placed the all at once solution to climate change out of reach for at least several years.

Instead, the United States and many other countries are likely to pursue a series of smaller policies all of which aim to reduce GHG emissions but individually have a marginal impact on atmospheric concentrations. These policies will appear in a wide variety of domains, ranging from subsidies for the installation of low carbon energy sources to regulations requiring energy efficiency standards in buildings, motor vehicles, and even vending machines to rebates for home insulation materials. Although many of these policies have other goals, their primary motivation is to reduce GHG emissions. However, these policies reduce GHG emissions at different rates and different costs.

In the presence of this heterogeneity and nearly limitless set of policies that reduce GHG emissions, how is government to set out a rational climate policy? The key step is to determine the monetized damages associated with an incremental increase in carbon emissions, which is referred to as the social cost of carbon (SCC).[1] It is intended to include (but is not limited to) changes in net agricultural productivity,

[1] Under Executive Order 12866, agencies in the Executive branch of the U.S. Federal government are required, to the extent permitted by law, "to assess both the costs and the benefits of the intended regulation and, recognizing that some costs and benefits are difficult to quantify, propose or adopt a regulation only upon a reasoned determination that the benefits of the intended regulation justify its costs."

human health, property damages from increased flood risk, and the value of ecosystem services.[2] Monetized estimates of the economic damages associated with carbon dioxide emissions allows the social benefits of regulatory actions that are expected to reduce these emissions to be incorporated into cost-benefit analyses.[3] Indeed as the Environmental Protection Agency begins to regulate greenhouse gases under the Clean Air Act, the SCC can help to identify the regulations where the net benefits are positive.

The United States Government (USG) recently selected four SCC estimates for use in regulatory analyses and has been using them regularly since their release. For 2010, the central value is $21 per ton of CO2 equivalent emissions.[4] The USG also announced that it would conduct sensitivity analyses at $5, $35, and $65. The $21, $5, and $35 values are associated with discount rates of 3%, 2.5%, and 5%, reflecting that much of the damages from climate change are in the future. The $65 value aims to represent the higher-than-expected impacts from temperature change further out in the tails of the SCC distribution. In particular, it is the SCC value for the 95th percentile at a 3 percent discount rate. These SCC estimates also grow over time based on rates endogenously determined within each model. For instance, the central value increases to $24 per ton of CO_2 in 2015 and $26 per ton of CO_2 in 2020.

I was involved in the interagency process that selected these values for the SCC and this talk summarizes these efforts.[5] The process was initiated in 2009 and completed in February 2010. It aimed to develop a defensible, transparent, and economically rigorous way to value reductions in carbon dioxide emissions that result from actions across the Federal government. Specifically, the goal was to develop a range of SCC values in a way that used a defensible set of input assumptions, was grounded in the existing literature, and allowed key uncertainties and model differences to transparently and consistently inform the range of SCC estimates used in the rulemaking process.

The intent of this lecture is to explain the central role of the social cost of carbon in climate policy, to summarize the methodology and process used by the interagency working group to develop values, and to identify key gaps so that researchers can fill these gaps. Indeed, the interagency working group explicitly aimed the current set of SCC estimates to be updated as scientific and economic understanding advances.

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[2] All values of the SCC are presented as the cost per metric ton of CO_2 emissions.

[3] Most regulatory actions are expected to have small, or “marginal,” impacts on cumulative global emissions, making the use of SCC an appropriate measure.

[4] All dollar values are expressed in 2007 dollars.

[5] This process was convened by the Council of Economic Advisers and the Office of Management and Budget, with regular input from other offices within the Executive Office of the President, including the Council on Environmental Quality, National Economic Council, Office of Energy and Climate Change, and Office of Science and Technology Policy. Agencies that actively participated included the Environmental Protection Agency, and the Departments of Agriculture, Commerce, Energy, Transportation, and Treasury.

Summary of the DICE model

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This report gives a brief summary of the DICE (Dynamic Integrated Climate-Economy) model, developed by William Nordhaus, which "integrate[s] in an end-to-end fashion the economics, carbon cycle, climate science, and impacts in a highly aggregated model that allow[s] a weighing of the costs and benefits of taking steps to slow greenhouse warming" (Nordhaus and Boyer 2000 p 5). Section 1 of this report recounts the major milestones in the development of DICE and its regionally disaggregated companion model, RICE. This section also serves as a convenient reference for more detailed expositions of the model and applications in the primary literature. Section 2 describes the basic structure of the most recently published version of DICE, and Section 3 describes some key aspects of the model calibration. Section 4 gives additional details on the climate damage function in DICE, and Section 5 gives a brief description of the most recently published version of the RICE model.

Historical development

The DICE integrated assessment model has been developed in a series of reports, peer reviewed articles, and books by William Nordhaus and colleagues over the course of more than thirty years. The earliest precursor to DICE was a linear programming model of energy supply and demand with additional constraints imposed to represent limits on the peak concentration of carbon dioxide in the atmosphere (Nordhaus 1977a,b).[2] The model was dynamic, in that it represented the time paths of the supply of energy from various fuels and the demand for energy in different sectors of the economy and the associated emissions and atmospheric concentrations of carbon dioxide. However, it included no representation of the economic impacts or damages from temperature or other climate changes. Later, Nordhaus (1991) developed a long-run steady-state model of the global economy that included estimates of both the costs of abating carbon dioxide emissions and the long term future climate impacts from climate change. This allowed for a balancing of the benefits and costs of carbon dioxide emissions to help determine the optimal level of near term controls. The analysis centered on the global average surface temperature, which was "…chosen because it is a useful index (in the nature of a sufficient statistic) of climate change that tends to be associated with most other important changes rather than because it is the most important factor in determining impacts" (Nordhaus 1991 p 930). The

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[1] Prepared for the EPA/DOE workshop, Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis, Washington DC, November 18-19, 2010. Please note that the views expressed in this paper are those of the author and do not necessarily represent those of the U.S. Environmental Protection Agency. No Agency endorsement should be inferred. Author's email: newbold.steve@epa.gov.

[2] While it has not been the focus of the DICE model, it should be emphasized that this type of cost-effectiveness framework is still useful. For example, if policy makers decide upon a 2 degree target, then the appropriate social cost of carbon to use is the shadow price associated with that path (Nordhaus, personal communication).

categories of climate damages that were represented in the model were associated with market sectors that accounted for roughly 13% of GDP in the United States.[3]

The DICE model was first presented in its modern form by Nordhaus (1992a,b), who described the new, fully dynamic Ramsey-type optimal growth structure of the model and the optimal time path of emission reductions and associated carbon taxes that emerged from it. The full derivation and extended description of the DICE model and a wider range of applications were presented in a book by Nordhaus (1994a). The next major advance involved disaggregating the model into ten different groups of nations to produce the RICE (Regional DICE) model, which allowed the authors to examine national-level climate policies and different strategies for international cooperation (Nordhaus and Yang 1996). An update and extended description of both RICE (now with eight regions) and DICE appeared in the book by Nordhaus and Boyer (2000). The next major update of DICE, modified to include a backstop technology that can replace all fossil fuels and whose price was projected to decline slowly over time, appeared in another book by Nordhaus (2008). Finally, Nordhaus (2010) described the most recent version of the RICE model, which adds an explicit representation of damages due to sea level rise.

In addition to the studies by Nordhaus and colleagues mentioned above, DICE has been adapted by other researchers to examine a wide range of issues related to the economics of climate change. A comprehensive review is well beyond the scope of this summary, so only a few examples are mentioned here. Pizer (1999) used DICE to compare carbon tax and a cap-and- trade-style policies under uncertainty. Popp (2005) modified DICE to include endogenous technical change. Baker et al. (2006) used DICE to examine the effects of technology research and development on global abatement costs. Hoel and Sterner (2007) modified the utility function in DICE to include a form of non-market environmental consumption that is an imperfect substitute for market consumption, and Yang (2008) used RICE in a cooperative game theory framework to examine strategies for international negotiations of greenhouse gas mitigation policies and targets.

Basic model structure

DICE2007 is a modified Ramsey-style optimal economic growth model, where an additional form of "unnatural capital"—the atmospheric concentration of CO_2—has a negative effect on economic output through its influence on the global average surface temperature. Global economic output is represented by a Cobb-Douglas production function using physical capital and labor as inputs. Labor is assumed to be proportional to the total global population, which grows exogenously over time. Total factor productivity also increases exogenously over time. The carbon dioxide intensity of economic production and the cost of reducing carbon dioxide emissions decrease exogenously over time. In each period a fraction of output is lost according to a Hicks-neutral climate change damage function. The output in each period is then divided between consumption, investment in the physical capital stock (savings), and expenditures on emissions reductions (akin to investment in the natural capital stock). DICE solves for the optimal path of savings and emissions reductions over a multi-century planning horizon, where the

[3] It should be emphasized that while this model and all subsequent versions of DICE necessarily make assumptions about climate and economic conditions in the far future, the important question is the extent to which current policies are robust to changes in assumptions about future variables (Nordhaus, personal communication).

objective to be maximized is the discounted sum of all future utilities from consumption. Total utility in each period is the product of the number of individuals alive and the utility of a representative individual with average income in that period. The period utility function is of the standard constant relative risk aversion (CRRA) form, and utilities in future periods are discounted at a fixed pure rate of time preference.

Calibration

The climate model in DICE2007 tracks the stocks and flows of carbon in three aggregate compartments of the earth system: the lower atmosphere, the shallow ocean, and the deep ocean. The transfer coefficients linking the flows among the compartments were "calibrated to fit the estimates from general circulation models and impulse-response experiments, particularly matching the forcing and temperature profiles in the MAGICC model" (Nordhaus 2008 p 54). The climate sensitivity parameter—the equilibrium change in global average surface temperature after a sustained doubling of atmospheric carbon dioxide concentration— was set to 3 degrees Celsius, which is near the middle of the range cited by the IPCC. The projected temperature change under the baseline scenario (with no climate controls for the first 250 years) is an increase in global average surface temperature of 3.2 degrees Celsius around year 2100 with a peak of around 6.5 degrees Celsius around year 2500.

The key economic growth and preference parameters of DICE2007 are calibrated as follows. The global population is projected to grow exogenously from around 6.5 billion in 2005 to 8.6 billion around 2200. Total factor productivity growth and the discount rate parameters were calibrated to match market returns in the early periods of the model: specifically, "We have chosen a time discount rate of 1½ percent per year along with a consumption elasticity of 2. With this pair of assumptions, the real return on capital averages around 5½ percent per year for the first half century of the projections, and this is our estimate of the rate of return on capital" (Nordhaus 2008 p 61).

The abatement cost function is specified such that the marginal abatement cost, measured as a fraction of output, increases roughly with the square of the fraction of emissions abated. The backstop price—the marginal cost of eliminating the last unit of emissions in each period—is $1,170 per metric ton of carbon in the first period and falls exponentially at a rate of 5% per decade to a long run value of $585 per metric ton of carbon. The climate damage function is specified such that for small temperature changes the fraction of output lost in each period increases with the square of the increase in temperature above the preindustrial average temperature.[4] The coefficient of the damage function is calibrated so that roughly 1.7% of global economic output is lost when the average global surface temperature is elevated by 2.5 degrees Celsius above the preindustrial average.

[4] The DICE2007 damage function has an "S-shape," so for very large temperature changes the fraction of output lost increases with temperature at a decreasing rate and asymptotes to one. However, it should be emphasized that the damage function is calibrated to damages in the range of 2 to 4 degrees Celsius. The extent of non-linearity beyond this range is unknown, so extrapolations beyond this point should not be considered reliable (Nordhaus, personal communication).

Damages

The globally aggregated climate damage function in DICE has been calibrated to match the sum of climate damages in all regions represented in the RICE model. The potential damages from climate change are divided into seven categories: agriculture, sea level rise, other market sectors, human health, nonmarket amenity impacts, human settlements and ecosystems, and catastrophes. A full recounting of the derivation of the damage functions in all categories is beyond the scope of this short summary, but to the give the reader a flavor for what is involved this section reviews three categories of damages: agriculture, heath, and catastrophes. This discussion draws heavily on Chapter 4 of Nordhaus and Boyer (2000), so the reader is referred there for more information.

Agriculture can serve as an illustrative example of some of the other categories not covered here. The basic strategy for calibrating the damage functions is to draw on estimates from previous studies of the potential economic losses in each category at a benchmark level of warming of 2.5 degrees Celsius, extrapolating across regions as necessary to cover data gaps in the literature. Some extrapolations were made using income elasticities for each impact category. As the authors explain, "United States agriculture can serve here as an example. Our estimate is that [the fraction of the value of agricultural output lost at 2.5 degrees Celsius] is 0.065 percent [based on Darwin et al. 1995]… The income elasticity of the impact index is estimated to be -0.1, based on the declining share of agriculture in output as per capita output rises" (Nordhaus and Boyer 2000 p 74-75).

The human health impacts of climate change were based on the effects of pollution and a broad group of climate-related tropical diseases including malaria and dengue fever. The increased mortality from warming in the summer and decreased mortality from warming in the winter were assumed to roughly offset and so were not included. The specification of the human health damage function involved "a regression of the logarithm of climate related [years of life lost] on mean regional temperature estimated form the data presented in Murray and Lopez [1996]" with judgmental adjustments "to approximate the difference among subregions that is climate related," and each year of life lost was valued at two years of per capita income (Nordhaus and Boyer 2000 p 80-82).

The damages from potential catastrophic impacts were estimated using results from a previous survey of climate experts by Nordhaus (1994b). The experts were asked for their best professional judgment of the likelihood of a catastrophe—specified as a 25 percent loss of global income indefinitely—if the global average surface temperature increased by 3 and by 6 degrees Celsius within 100 years. The averages of the survey responses were adjusted upward somewhat based on "[d]evelopments since the survey [that] have heightened concerns about the risks associated with major geophysical changes, particularly those associated with potential changes in thermohaline circulation" (Nordhaus and Boyer 2000 p 87). The probability of a 30 percent loss of global income indefinitely was assumed to be 1.2 and 6.8 percent with 2.5 and 6 degrees Celsius of warming, respectively. The percent of income lost was assumed to vary by region, and a coefficient of relative risk aversion equal to 4 was used to calculate the willingness to pay to avoid these risks in each region. The resulting "range of estimates of WTP lies between 0.45 and 1.9 percent of income for a 2.5$_{o}$C warming and between 2.5 and 10.8 percent of income for a 6$_{o}$C warming. It is assumed that this WTP has an income elasticity of 0.1" (Nordhaus and Boyer 2000 p 89).

Damages in the remaining categories were estimated in a similar vein, using a combination of empirical estimates from previous climate impact studies and professional judgments when needed to close the sometimes wide gaps in the literature. The table below shows the resulting global estimates of damages in each category in the 1999 version of RICE.

Damages as a percent of global output at 2.5°C of warming

	Output weighted	Population weighted
Agriculture	0.13	0.17
Sea level rise	0.32	0.12
Other market sectors	0.05	0.23
Health	0.10	0.56
Non-market amenities	-0.29	-0.03
Human settlements and ecosystems	0.17	0.10
Catastrophes	1.02	1.05
Total	1.50	1.88

(Nordhaus and Boyer 2000 p 91)

With damages in all categories estimated, the DICE damage function was then calibrated "so that the optimal carbon tax and emissions control rates in DICE-99 matched the projections of these variables in the optimal run of RICE-99" (Nordhaus and Boyer 2000 p 104).

Recent developments

Nordhaus (2010) presented results from an updated version of the RICE model. A major extension is a new sea level rise damage function, now explicitly modeled by region as a function of the global average sea level rise rather than rolled up in the aggregate damage function. "The RICE-2010 model provides a revised set of damage estimates based on a recent review of the literature [Toll 2009, IPCC 2007]. Damages are a function of temperature, SLR, and CO_2 concentrations and are region-specific. To give an idea of the estimated damages in the uncontrolled (baseline) case, those damages in 2095 are… 2.8% of global output, for a global temperature increase of 3.4°C above 1900 levels" (Nordhaus 2010 p 3). Other parameter updates include climate sensitivity, now set to 3.2 degrees Celsius, the elasticity of the marginal utility of income, now set to -1.5, and parameters that control economic growth rates, which are re-calibrated such that world per capita consumption grows by an average rate of 2.2% per year for the first 50 years.

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The PAGE09 model: Estimating climate impacts and the social cost of CO2

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Introduction

PAGE09 is a new version of the PAGE integrated assessment model that values the impacts of climate change and the costs of policies to abate and adapt to it. The model helps policy makers explore the costs and benefits of action and inaction, and can easily be used to calculate the social cost of CO2 (SCCO2) both today and in the future.

PAGE09 is an updated version of the PAGE2002 integrated assessment model. PAGE2002 was used to value the impacts and calculate the social cost of CO2 in the Stern review (Stern, 2007), the Asian Development Bank's review of climate change in Southeast Asia (ADB, 2009), and the EPA's Regulatory impact Analysis (EPA, 2010), and to value the impacts and costs in the Eliasch review of deforestation (Eliasch, 2008). The PAGE2002 model is described fully in Hope, 2006, Hope, 2008a and Hope, 2008b.

The update to PAGE09 been made to take account of the latest scientific and economic information, primarily in the 4th Assessment Report of the IPCC (IPCC, 2007). This short paper outlines the updated treatment of the science and impacts in the latest default version of the model, PAGE09 v1.7.

PAGE09 uses simple equations to simulate the results from more complex specialised scientific and economic models. It does this while accounting for the profound uncertainty that exists around climate change. Calculations are made for eight world regions, ten time periods to the year 2200, for four impact sectors (sea level, economic, non-economic and discontinuities) which cover all impacts, with the exception of socially contingent impacts such as massive forced migration and the threat of war, for which there are currently no economic estimates.

The treatment of uncertainty is at the heart of the model. In the calculation of the SCCO2, 45 inputs are specified as independent probability distributions; these typically take a triangular form, defined by a minimum, mode (most likely) and maximum value. The model is usually run 10000 times to build up full probability distributions of the scientific and economic results, such as the global mean temperature, the net present value of impacts and the SC CO2.

The full set of model equations and default inputs to the model are contained in a technical report available from the author. Initial results from the model are presented in a companion paper, 'The Social Cost of CO2 from the PAGE09 model'.

The changes made to PAGE2002 to create PAGE09 are outlined below under the following headings: Science, Impacts and Adaptation.

Science

Inclusion of Nitrous Oxide

The number of gases whose emissions, concentrations and forcing are explicitly modelled is increased from 3 in PAGE2002 to 4 in PAGE09. The forcing from N2O takes the same form as for

CH4, based on the square root of the concentration. The excess forcing from gases not explicitly modelled is now allowed to vary by policy.

Inclusion of transient climate response

In PAGE2002, the climate sensitivity is input directly as an uncertain parameter. The climate sensitivity in PAGE09 is derived from two inputs, the transient climate response (TCR), defined as the temperature rise after 70 years, corresponding to the doubling-time of CO2 concentration, with CO2 concentration rising at 1% per year, and the feedback response time (FRT) of the Earth to a change in radiative forcing (Andrews and Allen, 2008). Default triangular distributions for TCR and FRT in PAGE09 give a climate sensitivity distribution with a mean of 3 degC, and a long right tail, consistent with the latest estimates from IPCC, 2007.

Feedback from temperature to the carbon cycle

The standard PAGE2002 model contains an estimate of the extra natural emissions of CO2 that will occur as the temperature rises (an approximation for a decrease in absorption in the ocean and possibly a loss of soil carbon (Hope, 2006)). Recent model comparison exercises have shown that the form of the feedback in PAGE2002 works well for business as usual emissions, but overestimates concentrations in low emission scenarios (van Vuuren et al, 2009).

In PAGE09, the carbon cycle feedback (CCF) is introduced as a linear feedback from global mean temperature to a percentage gain in the excess concentration of CO2, to simulate the decrease in CO2 absorption on land and in the ocean as temperature rises (Friedlingstein et al, 2006). PAGE09 is much better than PAGE2002 at simulating the carbon cycle feedback results for low emission scenarios in Friedlingstein et al, 2006, van Vuuren et al, 2009.

Land temperature patterns by latitude

In PAGE2002, regional temperatures vary from the global mean temperature only because of regional sulphate forcing. However, geographical patterns of projected warming show greatest temperature increases over land (IPCC, 2007, ch10, p749), and a variation with latitude, with regions near the poles warming more than those near the equator (IPCC, 2007, ch10, figure 10.8 and supplementary material).

In PAGE09 the regional temperature is adjusted by a factor related to the effective latitude of the region, and one related to the land-based nature of the regions. The adjustment is calculated for each region using an uncertain parameter of the order of 1 degC representing the temperature increase difference between equator and pole, and the effective absolute latitude of the region, and an uncertain constant of the order of 1.4 representing the ratio between mean land and ocean temperature increases.

Explicit incorporation of sea level rise

In PAGE2002, sea level rise is only included implicitly, assumed to be linearly related to global mean temperature. This neglects the different time constant of the sea level response, which is longer than the surface air temperature response (IPPC, 2007, p823).

In PAGE09, sea level is modelled explicitly as a lagged linear function of global mean temperature (Grinsted et al, 2009). The IPCC has a sea level rise projection in 2100 of 0.4 – 0.7 m from pre-industrial times (IPCC , 2007, p409). A characteristic response time of between 500 and 1500 years in PAGE09 gives sea level rises compatible with these IPCC results.

Impacts

Impacts as a proportion of GDP

In PAGE2002, economic and non-economic impacts before adaptation are a polynomial function of the difference between the regional temperature and the tolerable temperature level, with regional weights representing the difference between more and less vulnerable regions. These impacts are then equity weighted, discounted at the consumption rate of interest and summed over the period from now until 2200. There are several issues with this representation, including the lack of an explicit link from GDP per capita to the regional weights, and the possibility that impacts could exceed 100% of GDP with unfavourable parameter combinations.

In PAGE09, extra flexibility is introduced by allowing the possibility of initial benefits from small increases in regional temperature (Tol, 2002), by linking impacts explicitly to GDP per capita and by letting the impacts drop below their polynomial on a logistic path once they exceed a certain proportion of remaining GDP to reflect a saturation in the vulnerability of economic and non-economic activities to climate change, and ensure they do not exceed 100% of GDP.

Figure 1

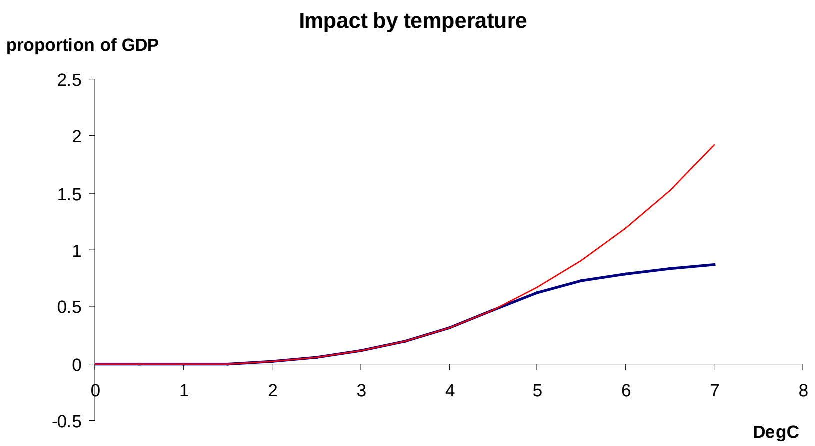


Figure 1 shows such an impact function, with initial benefits (IBEN) of 1% of GDP per degree, with impacts (W) of 4% of GDP at a calibration temperature (TCAL) of 2.5 degC, with a polynomial power (POW) of 3, and an exponent with income (IPOW) of -0.5. The impact function has a saturation(ISAT) starting at 50% of GDP, which keeps the impacts (blue line) below 100% of GDP even for the high temperatures shown. The red line shows what the impacts would be if they continued to follow the polynomial form without saturation.

Discontinuity impacts

As in PAGE2002, the risk of a large-scale discontinuity, such as the Greenland ice sheet melting, is explicitly modelled. In PAGE09 the losses associated with a discontinuity do not all occur immediately, but instead develop with a characteristic lifetime after the discontinuity is triggered (Lenton et al, 2008).

Equity weighting of impacts

In PAGE2002, impacts are equity weighted in a rather ad-hoc way, with the change in consumption increased in poor regions and decreased in rich ones.

PAGE09 uses the equity weighting scheme proposed by Anthoff et al (2009) which converts changes in consumption to utility, and amounts to multiplying the changes in consumption by

$$EQ(r,t) = (G(fr,0)/G(r,t))^{EMUC}$$

where G(r,t) is the GDP per capita in a region and year, G(fr,0) is today's GDP per capita in some focus region (which could be the world as a whole, but in PAGE09 is normally the EU), and EMUC is the negative of the elasticity of the marginal utility of consumption. This equity weighted damage is then discounted at the utility rate of interest, which is the PTP rate.

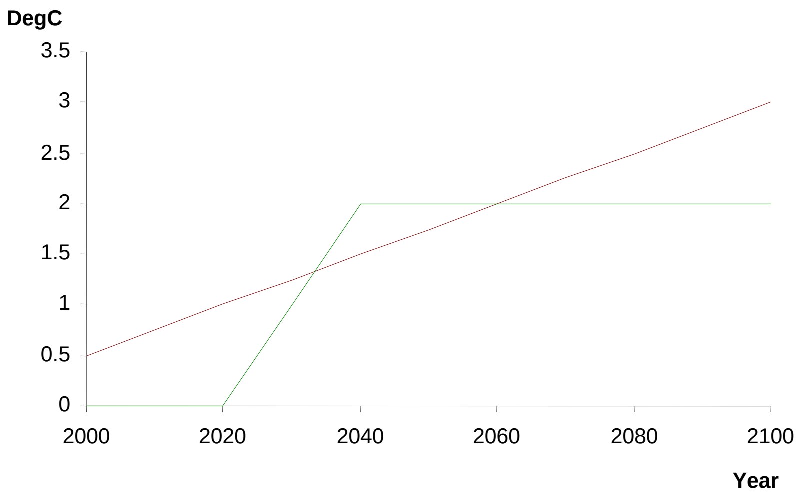
Adaptation

The speed and amount of adaptation is modelled as a policy decision in PAGE. This allows the costs and benefits of different adaptation decisions to be investigated. In PAGE2002, adaptation can increase the natural tolerable level of temperature change, and can also reduce any climate change impacts that still occur.

In PAGE09, there is assumed to be no natural tolerable temperature change, and adaptation policy is specified by seven inputs for each impact sector. The tolerable temperature is represented by the plateau, the start date of the adaptation policy and the number of years it takes to have full effect. The reduction in impacts is represented by the eventual percentage reduction, the start date, the number of years it takes to have full effect and the maximum sea level or temperature rise for which adaptation can be bought; beyond this, impact adaptation is ineffective. Both types of adaptation policy are assumed to take effect linearly with time. An adaptation policy in PAGE09 is thus defined by 7 inputs for 3 sectors for 8 regions, giving 168 inputs in all. This is a simplification compared to the 480 inputs in PAGE2002.

The green line in figure 2 shows an illustrative tolerable temperature profile over time in an impact sector that results from an adaptation policy that gives a tolerable temperature of 2 degC, starting in

Figure 2: Temperature and tolerable temperature by date (illustrative)



2020 and taking 20 years to implement fully. If the temperature rise is shown by the red line, there will be 0.5 degC of impacts in 2000, increasing to 1 deg C by 2020, then reducing to 0 from 2030 to 2060. After 2060 the impacts start again, reaching 1 deg C by 2100.

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FUND – Climate Framework for Uncertainty, Negotiation and Distribution

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FUND (the Climate Framework for Uncertainty, Negotiation and Distribution) is an integrated assessment model linking projections of populations, economic activity and emissions to simple greenhouse gas cycle, climate and sea-level rise models, and to a model predicting and monetizing welfare impacts. Climate change welfare impacts are monetized in 1995 dollars and are modelled over 16 regions. Modelled welfare impacts include agriculture, forestry, sea level rise, cardiovascular and respiratory disorders influenced by cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption from heating and cooling, water resources, unmanaged ecosystems and tropical and extratropical storms (Link and Tol, 2004). The source code, data, and a technical description of the model can be found at http://www.fund-model.org.

Essentially, *FUND* consists of a set of exogenous scenarios and endogenous perturbations. The model distinguishes 16 major regions of the world, viz. the United States of America, Canada, Western Europe, Japan and South Korea, Australia and New Zealand, Central and Eastern Europe, the former Soviet Union, the Middle East, Central America, South America, South Asia, Southeast Asia, China, North Africa, Sub-Saharan Africa, and Small Island States. Version 3.6, the latest version, runs to the year 3000 in time steps of one year.

The period of 1950-1990 is used for the calibration of the model, which is based on the *IMAGE* 100-year database (Batjes and Goldewijk, 1994). The period 1990-2000 is based on observations (http://earthtrends.wri.org). The 2000-2010 period is interpolated from the immediate past. The climate scenarios for the period 2010-2100 are based on the EMF14 Standardized Scenario, which lies somewhere in between IS92a and IS92f (Leggett *et al.*, 1992). The period 2100-3000 is extrapolated.

The scenarios are defined by varied rates of population growth, economic growth, autonomous energy efficiency improvements, and decarbonization of energy use (autonomous carbon efficiency improvements), as well as by emissions of carbon dioxide from land use change, methane emissions, and nitrous oxide emissions. FUND 3.5 introduced a dynamic biosphere feedback component that perturbates carbon dioxide emissions based on temperature changes.

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Emission reduction of carbon dioxide, methane and nitrous oxide is specified as in Tol (2006). Simple cost curves are used for the economic impact of abatement, with limited scope for endogenous technological progress and interregional spillovers (Tol, 2005).

The scenarios of economic growth are perturbed by the effects of climatic change. Climate-induced migration between the regions of the world causes the population sizes to change. Immigrants are assumed to assimilate immediately and completely with the respective host population.

The tangible welfare impacts are dead-weight losses to the economy. Consumption and investment are reduced without changing the savings rate. As a result, climate change reduces long-term economic growth, although consumption is particularly affected in the short-term. Economic growth is also reduced by carbon dioxide abatement measures. The energy intensity of the economy and the carbon intensity of the energy supply autonomously decrease over time. This process can be accelerated by abatement policies.

The endogenous parts of *FUND* consist of the atmospheric concentrations of carbon dioxide, methane and nitrous oxide, the global mean temperature, the effect of carbon dioxide emission reductions on the economy and on emissions, and the effect of the damages on the economy caused by climate change. Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted. The atmospheric concentration of carbon dioxide, measured in parts per million by volume, is represented by the five-box model of Maier-Reimer and Hasselmann (1987). Its parameters are taken from Hammitt *et al*. (1992).

The radiative forcing of carbon dioxide, methane, nitrous oxide and sulphur aerosols is determined based on Shine *et al*. (1990). The global mean temperature, *T*, is governed by a geometric build-up to its equilibrium (determined by the radiative forcing, *RF*), with a half-life of 50 years. In the base case, the global mean temperature rises in equilibrium by 3.0°C for a doubling of carbon dioxide equivalents. Regional temperature is derived by multiplying the global mean temperature by a fixed factor, which corresponds to the spatial climate change pattern averaged over 14 GCMs (Mendelsohn *et al.*, 2000). The global mean sea level is also geometric, with its equilibrium level determined by the temperature and a half-life of 50 years. Both temperature and sea level are calibrated to correspond to the best guess temperature and sea level for the IS92a scenario of Kattenberg *et al.* (1996).

The climate welfare impact module, based on Tol (2002a; Tol, 2002b) includes the following categories: agriculture, forestry, sea level rise, cardiovascular and respiratory disorders influenced by cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption from heating and cooling, water resources, unmanaged ecosystems and tropical and extratropical storms. Climate change related damages are triggered by either the rate of temperature change (benchmarked at 0.04°C/yr) or the level of temperature change (benchmarked at 1.0°C). Damages from the rate of temperature change slowly fade, reflecting adaptation (cf. Tol, 2002b).

In the model individuals can die prematurely due to temperature stress or vector-borne diseases, or they can migrate because of sea level rise. Like all welfare impacts of climate change, these effects are monetized. The value of a statistical life is set to be 200 times the annual per capita income.[2] The resulting value of a statistical life lies in the middle of the observed range of values in the literature (cf. Cline, 1992). The value of emigration is set to be three times the per capita income (Tol, 1995; Tol, 1996), the value of immigration is 40 per cent of the per capita income in the host region (Cline, 1992). Losses of dryland and wetlands due to sea level rise are modelled explicitly. The monetary value of a loss of one square kilometre of dryland was on average $4 million in OECD countries in 1990 (cf. Fankhauser, 1994). Dryland value is assumed to be proportional to GDP per square kilometre. Wetland losses are according to estimates from Brander et al. (2006). Coastal protection is based on cost-benefit analysis, including the value of additional wetland lost due to the construction of dikes and subsequent coastal squeeze.

Other welfare impact categories, such as agriculture, forestry, hurricanes, energy, water, and ecosystems, are directly expressed in monetary values without an intermediate layer of impacts measured in their 'natural' units (cf. Tol, 2002a). Modelled effects of climate change on energy consumption, agriculture, and cardiovascular and respiratory diseases explicitly recognize that there is a climatic optimum, which is determined by a variety of factors, including plant physiology and the behaviour of farmers. Impacts are positive or negative depending on whether the actual climate conditions are moving closer to or away from that optimum climate. Impacts are larger if the initial climate conditions are further away from the optimum climate. The optimum climate is of importance with regard to the potential impacts. The actual impacts lag behind the potential impacts, depending on the speed of adaptation. The impacts of not being fully adapted to new climate conditions are always negative (cf. Tol, 2002b).

The welfare impacts of climate change on coastal zones, forestry, hurricanes, unmanaged ecosystems, water resources, diarrhoea, malaria, dengue fever, and schistosomiasis are modelled as simple power functions. Impacts are either negative or positive, and they do not change sign (cf. Tol, 2002b).

Vulnerability to climate change changes with population growth, economic growth, and technological progress. Some systems are expected to become more vulnerable, such as water resources (with population growth) and heat-related disorders (with urbanization), or more valuable, such as ecosystems and health (with higher per capita incomes). Other systems are projected to become less vulnerable, such as energy consumption (with technological progress), agriculture (with economic growth) and vector- and water-borne diseases (with improved health care) (cf. Tol, 2002b).

In the Monte Carlo analyses, most model parameters (including parameters for the physical components as well as the economic valuation components) are varied. The probability density functions are mostly based on expert guesses, but where possible "objective" estimates were used. Parameters are assumed to vary independently of one another, except when there are calibration or accounting constraints. "Preference parameters" like the discount rate or the parameter of risk aversion are not varied in the Monte Carlo analysis. Details of the Monte Carlo analysis can be found on *FUND*'s website at http://www.fund-model.org.

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[2] Note that this implies that the monetary value of health risk is effectively discounted with the pure rate of time preference rather than with the consumption rate of discount (Horowitz, 2002). It also implies that, after equity weighing, the value of a statistical life is equal across the world (Fankhauser *et al.*, 1997).

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Climate Damages in the MIT IGSM

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Integrated assessment models (IAMs) have proven useful for analysis of climate change because they represent the entire inhabited earth system, albeit typically with simplified model components that are reduced form or more highly aggregated than for example, high resolution coupled atmosphere-ocean-land general circulation models. The MIT Integrated Global System Model has been developed to retain the flexibility to assemble earth system models of variable resolution and complexity, however, even at its simplest it remains considerably more complex than most other IAMs. In its simplest formulation it retains a full coupled general circulation model of the ocean and atmosphere. Solved recursively, it solution time for a 100-year integration on a single node of computer cluster is on the order of 24-36 hours, compared with seconds or minutes for other IAMs. In that form it is not numerical feasible to solve the whole system as a fully dynamic optimizing model to find an optimal cost-benefit solution as with the DICE, PAGE, or FUND models. Indeed, inclusion of climate damages is still a work in progress in the MIT IGSM. The slow progress relative to other efforts stems from a commitment to represent explicitly the physical impacts of climate ad environmental change on activities (e.g. crop yields, water availability, coastal, inundation, ecosystem processes and functioning, health outcomes, etc.) and represent market response to these outcomes and value that response consistent with projections of resource prices as they are projected to change in the future with economic growth and under different policies to mitigate greenhouse gas emissions. This is in contrast to most of the optimizing models where climate damages are estimated as a reduced form relationship in dollars of economic loss as a function of mean global temperature change as a sufficient indicator of many dimensions of climate change, and where the damage function is itself completely independent and separable from the economy as it affects energy use and greenhouse gas emissions. The MIT IGSM is not designed to run well if the purpose is to estimate a net present value social cost of carbon. The IGSM is best seen as complementary to such efforts, and probably the focus on uncertainty in future climate outcomes is one of the areas where it can make the most contribution t the social cost of carbon discussion.

Computationally efficient versions of the IGSM have been assembled for simulating large ensembles to study uncertainty (Sokolov et al., 2009; Webster et al., 2009). Less complete but more highly-resolved model components can be combined where research demands them, such as in the study of the climate effect of aerosols (Wang, 2009; Wang et al., 2009a,b), changes in atmospheric composition and human health (Selin et al., 2009a) or agricultural impacts and land use change (Reilly, et al. 2007; Felzer et al., 2005; Melillo et al., 2009). The IGSM framework encompasses the following components:

- global economic activity resolved for large countries and regions that projects changes in human activities as they effect the earth system including emissions of pollutants and radiatively active substances and changes in land use and land cover;
- earth system modules linked to the macroeconomy that address effects of climate and environmental change on human activity, adaptation, and their consequences for the macroeconomy (this includes modules that represent water use and land use at

disaggregated spatial scales, energy and coastal infrastructure again at disaggregate spatial scales, and demography, urbanization, urban air chemistry, and epidemiological relationships that relate environmental change to human health);

- the natural and managed land system including vegetation, hydrology, and biogeochemistry as affected by human activity, environmental change and feedbacks on climate and atmospheric composition;
- the circulation and biogeochemistry of the ocean including its interactions with the atmosphere, and representations of physical and biological oceanic responses to climate change; and
- the circulation and chemistry of the atmosphere including its role in radiative forcing, and interactions with the land and ocean that determine climate change.

The suite of models that have been employed in this framework and their capabilities are briefly described below.

Human Drivers and Analysis of Impacts

Human activities as they contribute to environmental change or are affected by it are represented in multi-region, multi-sector models of the economy that solves for the prices and quantities of interacting domestic and international markets for energy and non-energy goods as well as for equilibrium in factor markets. The MIT Emissions Predictions and Policy Analysis (EPPA) model (Paltsev et al., 2005) covers the world economy. It is built on the GTAP dataset (maintained at Purdue University) of the world economic activity augmented by data on the emissions of greenhouse gases, aerosols and other relevant species, and details of selected economic sectors. The GTAP database allows flexibility to represent the world economy with greater country or sector detail (the data set has 112 countries/regions and 57 economic sectors) that we aggregate further for numerical efficiency. The model projects economic variables (GDP, energy use, sectoral output, consumption, etc.) and emissions of greenhouse gases (CO2, CH4, N2O, HFCs, PFCs and SF6) and other air pollutants (CO, VOC, NOx, SO2, NH3, black carbon, and organic carbon) from combustion of carbon-based fuels, industrial processes, waste handling, and agricultural activities.

The model has been augmented with supplemental physical accounts to link it with the earth system components of the IGSM framework. To explore land use and environmental consequences, the EPPA model (Gurgel, et al., 2007; Antoine, et al.,2008) is coupled with the Terrestrial Ecosystem Model (Melillo et al., 2009). The linkage allows us to examine the ability of terrestrial ecosystems to supply biofuels to meet growing demand for low-emissions energy sources along with the growing demand for food, and to assess direct and indirect emissions from an expanded cellulosic bioenergy program. The approach generates worldwide land-use scenarios at a spatial resolution of 0.5º latitude by 0.5º longitude that varies with climate change. To analyze the economic impacts of air pollution, the EPPA model is extended to include pollution-generated health costs, which reduce the resources available to the rest of the economy (Nam et al., 2009; Selin et al., 2009a). The model captures the amount of labor and leisure lost and additional medical services required due to acute and chronic exposure to pollutants. The GTAP database allows considerable flexibility to represent the world economy with greater country or sector detail (the underlying data has 112 countries/regions and 57 economic sectors). To assess distributional and regional impacts of carbon policy in the US, we use a model that is based on a state-level database and resolves large U.S. states and multi-state regions and households of several income classes. The U.S. Regional Energy Policy (USREP) model (Rausch et al., 2009; 2010) is nearly identical in structure to the EPPA model, except that it models states and multi-state regions in the US instead of countries and multi-country regions. The main difference from the EPPA model is the foreign sector that is represented as export supply and import demand functions rather than a full representation of foreign economies. This sacrifice of global coverage allows explicit modeling of distributional details of climate legislation and linking the USEP model to very detailed electricity dispatch models. Efforts, under separate funding, to integrate the USREP database into the GTAP base to provide a complete representation of trade are underway. Physical impacts of environmental change have been included in the model as a feedback by identifying factors (land productivity as it affects crops, livestock and forests) or sectors affected by climate or by introducing additional household production sectors (household health services that uses leisure and medical services). Thus, the approach is to work with underlying input-output and Social Accounting Matrix (SAM) that is the basis for the economic model (Matus, et al., 2008). This provides a framework for potentially linking other impacts such as coastal (Franck et al., 2010a,b, 2010; Sugiyama, et al., 2008), agriculture (Reilly et al., 2007), health (Selin, et al., 2009; Nam et al., 2010), or water (Strzepek et al., 2010) impacts.

Hydrology and Water Management

Research on components representing water management are aimed at linking hydrological changes projected by the atmospheric component of the IGSM to impacts of those changes on water availability and use for irrigation, energy, industry and households, and in-stream ecological services. These demands are driven by macroeconomic changes and changes in water supply and will in turn affect the economy as represented in the EPPA and the USREP models. Techniques have been developed to take IGSM 2-D GCM outputs and use results from the IPCC AR-4 3-D GCMs to provide IGSM-generated 3-D climates to the hydrology component of the IGSM-Land Surface Model (NCAR Community Land Model, CLM) to project runoff. Tests have been conducted for the US, where adequate data are available, to determine the spatial resolution needed to provide reliable estimates of runoff using CLM. A Water Resources System (WRS) model has been adapted from and further developed in collaboration with the International Food Policy Research Institute (IFPRI) to represent river reaches and natural and management components that affect stream-flow. The major natural components are wetlands, unmanaged lakes, groundwater aquifers and flood plains. The major managed components are reservoirs and managed lakes, and water diversions for irrigation, cooling in thermal power plants, and industrial and household needs. Constraints on use to preserve in-stream ecological water requirements can be imposed.

A series of models were adapted and developed to represent water use. These include a crop growth model (CLICROP) developed to be able to run at 2° latitude-longitude grid resolution while retaining the accuracy of a 0.5° resolution, thereby improving numerical efficiency of the modeling system (Strzepek et al., 2010a). A model of Municipal and Industrial water demand driven by per capita GDP was developed jointly with the University of Edinbough (Hughes et al., 2010; Strzepek et al., 2010a). To investigate changes in thermal electric cooling water demands, a geospatial methodology based on energy generation and geo-hydroclimatic variables has been developed (Strzepek et al., 2010b). An assessment of environmental flow requirements to assure aquatic ecosystem viability has been undertaken and an approach for using the IGSM was selected (Strzepek

& Boehlert, 2010; Strzepek et al., 2010a). These developments provide the foundation for completing linkages of the WRS with other IGSM components.

Atmospheric Dynamics and Physics

Research utilizing the IGSM framework has typically included a 2-D atmospheric (zonally-averaged statistical dynamical) component based on the Goddard Institute for Space Studies (GISS) GCM. The IGSM version 2.2 couples this atmosphere with a 2D ocean model (latitude, longitude) with treatment of heat and carbon flows into the deep ocean (Sokolov et al, 2005). The IGSM version 2.3 (where 2.3 indicates the 2-D atmosphere/full 3-D ocean GCM configuration) (Sokolov et al., 2005; Dutkiewicz et al., 2005) is a fully-coupled Earth system model that allows simulation of critical feedbacks among its various components, including the atmosphere, ocean, land, urban processes and human activities. A limitation of the IGSM2.3 is the above 2-D (zonally averaged) atmosphere model that does not permit direct regional climate studies. For investigations requiring 3-D atmospheric capabilities, the National Center for Atmospheric Research (NCAR) Community Atmosphere Model version 3 (CAM3) (Collins et al., 2006) has been used with offline coupling.

The IGSM2.3 provides an efficient tool for generating probabilistic distributions of sea surface temperature (SST) and sea ice cover (SIC) changes for the 21st century under varying emissions scenarios, climate sensitivities, aerosol forcing and ocean heat uptake rates. Even though the atmospheric component of the IGSM2.3 is zonally-averaged, it provides heat and fresh-water fluxes separately over the open ocean and over sea ice, as well as their derivatives with respect to surface temperature. This resolution allows the total heat and fresh-water fluxes for the IGSM2.3 oceanic component to vary by longitude as a function of SST so that, for example, warmer ocean locations undergo greater evaporation and receive less downward heat flux.

In offline coupling between the IGSM2.3 and CAM3, the 3-D atmosphere is driven by the IGSM2.3 SST anomalies with a climatological annual cycle taken from an observed dataset (Hurrell et al., 2008), instead of the full IGSM2.3 SSTs, to provide a better SST annual cycle, and more realistic regional feedbacks between the ocean and atmospheric components. This approach yields a consistent regional distribution and climate change over the 20th century as compared to observational datasets, and can then be used for simulations of the 21st century.

Urban and Global Atmospheric Chemistry and Aerosols

The model of atmospheric chemistry includes an analysis of all the major climate-relevant reactive gases and aerosols at urban scales coupled to a model of the chemistry of species exported from urban/regional areas (plus the emissions from non-urban areas) at global scale. For calculation of the atmospheric composition in non-urban areas, the atmospheric dynamics and physics model is linked to a detailed 2-D zonal-mean model of atmospheric chemistry. The atmospheric chemical reactions are thus simulated in two separate modules: one for the sub-grid-scale urban chemistry and one for the 2-D model grid. In addition, offline studies also utilize the 3-D capabilities of the CAM3 as noted above, as well as the global Model of Atmospheric Transport and Chemistry (MATCH; *Rasch et al.,* 1997), and the GEOS-Chem global transport model (http://geos-chem.org/).

Global Atmospheric Chemistry: Modeling of atmospheric composition at global scale is by the above 2-D zonal-mean model with the continuity equations for trace constituents solved in mass conservative or flux form (Wang et al., 1998). The model includes 33 chemical species including black carbon aerosol, and organic carbon aerosol, and considers convergences due to transport, convection, atmospheric chemical reactions, and local production/loss due to surface emission/deposition. The scavenging of carbonaceous and sulfate aerosol species by precipitation is included using a method based on a detailed 3-D climate-aerosol-chemistry model (Wang, 2004) that has been developed in collaboration with NCAR. The interactive aerosol-climate model is used offline to model distributions of key chemical species, such as those utilized in the development of the urban air chemistry model.

Urban Air Chemistry: A reduced-form urban chemical model that can be nested within coarser-scale models has been developed and implemented to better represent the sub-gridscale urban chemical processes that influence air chemistry and climate (Cohen & Prinn, 2009). This is critical both for accurate representation of future climate trends and for our increasing focus on impacts, especially to human health and down-wind ecosystems. The MIT Urban Chemical Metamodel (UrbanM) is an update of our Mayer et al. (2000) model, and applies a third-order polynomial fit to the CAMx regional air quality model (ENVIRON, 2008) for 41 trace gases and aerosols for a 100 km x 100 km urban area. While a component of the IGSM, the urban modular UrbanM is also designed to facilitate inclusion in a number of other global atmospheric models. It has recently been embedded in the MIT interactive climate-aerosol simulation based on CAM3 in order to assess its influence on the concentration and distribution of aerosols in Asia (Cohen et al., 2009). Work is underway to further test the sensitivity of the probabilistic uncertainty results with the IGSM2.2/2.3 to this improved representation of urban chemistry. The UrbanM is presently being benchmarked in a case study of the Northeast U.S., and embedded in a global 3-D chemistry-climate model including a detailed chemical mechanism (NCAR CAM-Chem).

Chemistry-Climate-Aerosol Component: A 3-D interactive aerosol-climate model has been developed at MIT in collaboration with NCAR based on the finite volume version of the Community Climate ystem Model (CCSM3; Collins et al., 2006). Focused on analysis of aerosols, this companion sub-model is not yet integrated into the IGSM but serves as a step toward overcoming the limitations for analysis of regional issue using the IGSM 2-D atmosphere configuration. The modeled aerosols include three types of sulfate, two external mixtures of black carbon (BC), one type of organic carbon, and one mixed state (comprised primarily of sulfate and other compounds coated on BC); each aerosol type has a prognostic size distribution (Kim et al., 2008). The model incorporates such processes as aerosol nucleation, diffusive growth, coagulation, nucleation and impaction scavenging, dry deposition, and wet removal. It has been used to investigate the global aerosol solar absorption rates (Wang et al., 2009a) and the impact of absorbing aerosols on the Indian summer monsoon (Wang et al., 2009b). The UrbanM has recently been introduced into this model to study the roles of urban processing in global aerosol microphysics nd chemistry and to compute the abundance and radiative forcing of anthropogenic aerosols (Cohen et al., 2010). This effort also serves as the first step toward introducing the full UrbanM into the 3-D aerosol-chemistry-climate framework.

Ocean Component

The IGSM framework retains the capability to represent ocean physics and biogeochemistry in several different ways depending onthe question to be addressed. It can utilize either the 2-D (latitude-longitude) mixed-layer anomaly-diffusing ocean model or the fully 3-D ocean general circulation model (GCM). The IGSM with the 2-D ocean is more computationally efficient and more flexible for studies of uncertainty in climate response. In applications that need to account for atmosphere-ocean circulation interactions, or for more detailed studies involving ocean biogeochemistry, the diffusive ocean model is replaced by the fully 3D ocean GCM component.

2-D Ocean Model: The IGSM2.2 has a mixed-layer anomaly-diffusing ocean model with a horizontal resolution of 4º in latitude and 5º in longitude. Mixed-layer depth is prescribed based on observations as a function of time and location. Vertical diffusion of anomalies into the deep ocean utilizes a diffusion coefficient that varies zonally as well as meridionaly. The model includes specified vertically-integrated horizontal heat transport by the deep oceans, and allows zonal as well as meridional transport. A thermodynamic ice module has two layers and computes the percentage of area covered by ice and ice thickness, and a diffusive ocean carbon module is included (Sokolov et al, 2005; Holian et al., 2001; Follows et al. 2006).

3-D Ocean General Circulation Model: The IGSM2.3 ocean component is based on a state-of-the-art 3D MIT ocean GCM (Marshall et al., 1997). Embedded in the ocean model is a thermodynamic sea-ice module (Dutkiewicz et al., 2005). The 3D ocean component is currently configured in either a coarse resolution (4° by 4° horizontal, 15 layers in the vertical) or higher resolution (2° by 2.5°, 23 layers; or alternate configuration with higher resolution in the topics) depending on the focus of study and the computational resources available. The efficiency of ocean heat uptake can be varied (e.g., Dalan et al. 2005) and the coupling of heat, moisture, and momentum can be modified for process studies (e.g., Klima 2008). In addition, a biogeochemical component with explicit representation of the cycling of carbon, phosphorus and alkalinity can be incorporated. Export of organic and particulate inorganic carbon from surface waters is parameterized and biological productivity is modelle as a function of available nutrients and light (Dutkiewicz et al., 2005). Air-sea exchange of CO2 allows feedback between the ocean and atmosphere components. An additional module with explicit representation of the marine ecosystem (Follows et al., 2007) has been introduced in an “offline” (i.e. without full feedbacks to the full IGSM) configuration (see further discussion in Section 4.2.3).

Land and Vegetation Processes

The Global Land System (GLS, Schlosser et al., 2007) of the IGSM links biogeophysical, ecological, and biogeochemical components: (1) the NCAR Community Land Model (CLM), which calculates the global, terrestrial water and energy balances; (2) the Terrestrial Ecosystems Model (TEM) of the Marine Biological Laboratory, which simulates carbon (CO2) fluxes and the storage of carbon and nitrogen in vegetation and soils including net primary production and carbon sequestratio or loss; and (3) the Natural Emissions Model (NEM), which simulates fluxes of CH4 and N2O, and is now embedded within TEM. A recent augmentation to the GLS enables a more explicit treatment of agricultural processes and a treatment of the managed waer systems (Strzepek et al., 2010a). The linkage between econometrically based decisions regarding land use (from EPPA) and plant productivity from TEM has been enhanced (Cai et al., 2010). And the treatment of migration of plant species to include meteorological constraints (i.e. winds) to seed dispersal has been enhanced (Lee et al., 2009, 2010a,b). The representation of natural and vegetation processes also includes a diagnosis of the expansion of lakes and changes of methne emissions from thermokarst lake expansion/degradation (Gao et al., 2010; Schlosser et al., 2010). In addition, continuing updates to CLM and TEM are also incorporated into the GLS framework. In all these applications, the GLS is operating under a range of spatial resolutions (from zonal to gridded as low as 0.5º), and is configured in its structural detail to accommodate various levels of process-oriented research both in a coupled framework within the IGSM as well as in standalone studies (i.e. with prescribed atmospheric forcing).

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Modeling the Impacts of Climate Change: Elements of a Research Agenda

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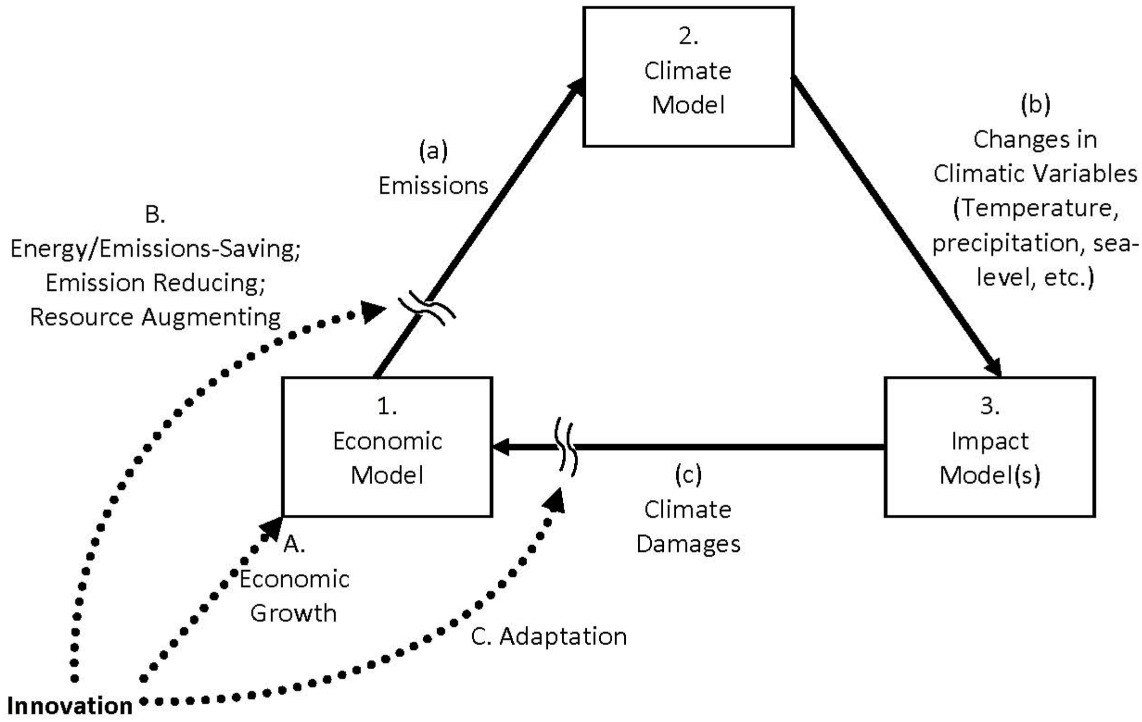
Introduction: What is an IAM?

As illustrated in Figure 1, an integrated assessment model (IAM) of climate change is typically constructed from three interlinked sub-models, an economic model (1), a climate model (2) and an impacts model (3). It is logical to begin with the economic sub-model, which is responsible for generating time-paths of global emissions of greenhouse gases (GHGs—principally carbon dioxide, CO_2) (a). These serve as inputs to the climate submodel, which uses them to project changes in the magnitude of meteorological variables such as temperature, precipitation or sea level rise (b). Finally, the changes in climate parameters are translated into projections of global- or regional-scale economic losses by an impacts sub-model, whose primary role is to capture the feedback effect of dangerous near-term anthropogenic interference with the climate on economic activity over the longterm future (c).

Innovation is a key modulator of the clockwise circulation of the feedback loop in the figure. Improvements in the productivity of labor induce more rapid growth and increase the demand for fossil energy resources, which has a first-order amplifying effect on emissions (A). Energy- or emissions-saving technological progress tends to depress the emission intensity of the economy, slowing the rate of increase in fossil fuel use; conversely, productivity improvements in energy resource extraction lower the price of fossil fuels and induce substitution toward them, increasing emissions (B). Lastly, we can imagine that there may be innovations that boost the effectiveness of defensive expenditures undertaken in response to the threat of climate damages, or investments in creating new knowledge that enables humankind to mitigate some climate damages (C). This last category is the most speculative, as impacts will manifest themselves several decades in the future, when the state of technology is likely to be quite different from today.

Figure 1: Integrated Assessment of Climate Change and the Effects of Innovation



Land of Cockaigne: An IAM with Regional, Sectoral and Climate Impact Detail

Imagine that there were relatively few constraints to either our computational resources or our ability to foresee the impacts of climate change. In such a world, what would an IAM look like? We could then specify a RICE- or AD-WITCH-type IAM that resolved (a) the detailed sectoral structure of production in various regions, (b) the effects of climate impacts on the productivity of those sectors, (c) the manner in which different impact endpoints combined to generate the resultant productivity effects, and (d) the response of the full range of impacts to changes in climatic variables at regional scale.

Let us write down such a model, and exploit its structure to assess the implications for the social cost of carbon. Define the following nomenclature:

Set indexes:

$t = \{0,...,T\}$	Time periods
$l = \{0,...,L\}$	World regions
$j = \{0,...,N\}$	Industry sectors
$m = \{0,...,M\}$	Meteorological characteristics
$f = \{0,...,F\}$	Climate impact endpoints

Control variables:

$q^E_{j,l,t}$	Sectoral energy input
$q^K_{j,l,t}$	Sectoral capital input
$Q^C_{l,t}$	Aggregate consumption

$Q^{I}_{l,t}$	Aggregate jelly capital investment
$a^{f}_{j,l,t}$	Region-, sector- and impact-specific averting expenditure
$v^{f}_{j,l,t}$	Region-, sector- and impact-specific adaptation investment

Economic state variables:

W	Welfare (model objective)
$q^{Y}_{j,l,t}$	Net sectoral product
$Q^{Y}_{l,t}$	Aggregate net regional product
$Q^{E}_{l,t}$	Aggregate regional energy use
P^{E}_{t}	Global marginal energy resource extraction cost
$Q^{K}_{l,t}$	Stock of aggregate jelly capital
$x^{f}_{j,l,t}$	Stock of region-, sector- and impact-specific adaptation capital

Environmental state variables:

G_{t}	Global stock of atmospheric GHGs
$M^{m}_{l,t}$	Region-specific meteorological variables
$z^{f}_{j,l,t}$	Region-, sector-, and impact-specific endpoint indexes
$\Lambda_{j,l,t}$	Region- and sector-specific damage induced productivity losses

Functional relationships:

Ξ	Global intertemporal welfare
U_{l}	Regional intratemporal utility
Φ_{l}	Regional aggregate production functions
$\Psi_{j,l}$	Sectoral production functions
Θ	Global energy supply function
ε	Global atmospheric GHG accumulation
Y^{m}_{l}	Regional climate response functions
$\varsigma^{I}_{l,t}$	Regional and sectoral climate impacts functions
$\lambda_{j,l}$	Regional and sectoral damage functions

1. Economic Sub-Model

Objective:

$$\max_{Q^{C}_{\ell,t},\, q^{E}_{j,\ell,t},\, q^{K}_{j,\ell,t}} \mathscr{W} = \sum_{t=0}^{T} \beta^{t}\, \Xi\left[U_{1}\left[Q^{C}_{1,t}\right], \ldots, U_{\mathscr{L}}\left[Q^{C}_{\mathscr{L},t}\right]\right] \quad (1a)$$

Aggregate net regional product:

$$Q^{Y}_{\ell,t} = \Phi_{\ell}\left[q^{Y}_{1,\ell,t}, \ldots, q^{Y}_{\mathscr{N},\ell,t}\right]$$

(1b)

Sectoral net regional product = Climate loss factor × Sectoral gross regional product, produced from energy and capital:

$$q^{Y}_{j,\ell,t} = \Lambda_{j,\ell,t} \cdot \psi_{j,\ell} \left[q^{E}_{j,\ell,t}, q^{K}_{j,\ell,t} \right] \tag{1c}$$

Intraregional and intratemporal market clearance for energy:

$$\sum_{j=1}^{\mathcal{N}} q^{E}_{j,\ell,t} = Q^{E}_{\ell,t} \tag{1d}$$

Intraregional and intratemporal market clearance for jelly capital:

$$\sum_{j=1}^{\mathcal{N}} q^{K}_{j,\ell,t} = Q^{K}_{\ell,t} \tag{1e}$$

Aggregate regional absorption constraint:

$$Q^{C}_{\ell,t} = Q^{Y}_{\ell,t} - Q^{I}_{\ell,t} - P^{E}_{t} Q^{E}_{\ell,t} - \sum_{f=1}^{\mathcal{F}} \sum_{j=1}^{\mathcal{N}} \left(a^{f}_{j,\ell,t} + v^{f}_{j,\ell,t} \right) \tag{1f}$$

Global energy trade and marginal resource extraction cost:

$$P^{E}_{t} = \Theta \left[\sum_{\ell=1}^{\mathcal{L}} \sum_{s=0}^{t} Q^{E}_{\ell,s} \right] \tag{1g}$$

Regional jelly capital accumulation:

$$Q^{K}_{\ell,t+1} = Q^{I}_{\ell,t} + (1 - \vartheta^{K}) Q^{K}_{\ell,t} \tag{1h}$$

Accumulation of impact-, sector- and region-specific adaptation capital:

$$x^{f}_{j,\ell,t+1} = v^{f}_{j,\ell,t} + (1 - \vartheta^{f}) x^{f}_{j,\ell,t} \tag{1i}$$

2. Climate Sub-Model

Global atmospheric GHG accumulation:

$$G_{t+1} = \mathcal{E} \left[\sum_{\ell} Q^{E}_{\ell,t}, G_{t} \right] \tag{2a}$$

Regional meteorological effects of global atmospheric GHG concentration:

$$M^{m}_{\ell,t} = \Upsilon^{m}_{\ell} \left[G_{t} \right] \tag{2b}$$

3. Impacts Sub-Model

Physical climate impacts by type, sector and region:

$$z^{f}_{j,\ell,t} = \zeta^{f}_{j,\ell} \left[M^{1}_{1,0}, \ldots, M^{\mathcal{M}}_{1,0}; \ldots; M^{1}_{\mathcal{L},t}, \ldots, M^{\mathcal{M}}_{\mathcal{L},t} \right] \tag{3a}$$

Climate damages:

$$\Lambda_{j,\ell,t} = \lambda_{j,\ell} \left[z^{1}_{j,\ell,t}, \ldots, z^{\mathcal{F}}_{j,\ell,t}; a^{1}_{j,\ell,t}, \ldots, a^{\mathcal{F}}_{j,\ell,t}; x^{1}_{j,\ell,t}, \ldots, x^{\mathcal{F}}_{j,\ell,t} \right] \tag{3b}$$

From the point of view of period t*, the condition for optimal extraction of carbon-energy is:

$$\frac{\partial \mathscr{W}}{\partial Q^E_{\ell^\star,t^\star}} \Big/ \frac{\partial \mathscr{W}}{\partial Q^C_{\ell^\star,t^\star}} = \underbrace{\sum_{j=1}^{\mathscr{N}} \left(\frac{\partial \phi_{\ell^\star}}{\partial q^Y_{j,\ell^\star,t^\star}} \frac{\partial \psi_{j,\ell^\star}}{\partial q^E_{j,\ell^\star,t^\star}} \frac{\partial q^E_{j,\ell^\star,t^\star}}{\partial Q^E_{\ell^\star,t^\star}} \right)}_{\text{I. Current marginal benefit}} - \underbrace{P^E_{t^\star}}_{\substack{\text{II. Current marginal} \\ \text{extraction cost}}}$$

$$- \underbrace{\sum_{t=t^\star}^{T} \beta^{t-t^\star} \sum_{\ell=1}^{\mathscr{L}} \left(\frac{\partial \Xi}{\partial U_\ell} \frac{\partial U_\ell}{\partial Q^C_{\ell,t}} \frac{\partial \Theta}{\partial Q^E_{\ell^\star,t^\star}} Q^E_{\ell,t} \right) \Big/ \left(\frac{\partial \Xi}{\partial U_{\ell^\star}} \frac{\partial U_{\ell^\star}}{\partial Q^C_{\ell^\star,t^\star}} \right)}_{\text{III. Resource stock effect of contemporaneous energy use}}$$

$$\underbrace{\begin{aligned} &+ \sum_{t=t^\star+1}^{T} \beta^{t-t^\star} \frac{\partial \mathcal{E}}{\partial Q^E_{\ell^\star,t^\star}} \Big/ \left(\frac{\partial \Xi}{\partial U_{\ell^\star}} \frac{\partial U_{\ell^\star}}{\partial Q^C_{\ell^\star,t^\star}} \right) \\ &\times \sum_{\ell=1}^{\mathscr{L}} \left\langle \frac{\partial \Xi}{\partial U_\ell} \frac{\partial U_\ell}{\partial Q^C_{\ell,t}} \sum_{j=1}^{\mathscr{N}} \left\{ \frac{\partial \phi_\ell}{\partial q^Y_{j,\ell,t}} \psi_{j,\ell,t} \sum_{f=1}^{\mathscr{F}} \left[\frac{\partial \lambda_{j,\ell}}{\partial z^f_{j,\ell,t}} \sum_{m=1}^{\mathscr{M}} \left(\frac{\partial \zeta^f_{j,\ell}}{\partial M^m_{\ell,t}} \frac{\partial Y^m_\ell}{\partial G_t} \right) \right] \right\} \right\rangle \end{aligned}}_{\text{IV. Present value of future marginal climate damage (N.B. } \partial q^Y / \partial \Lambda < 0 \text{ in general)}}$$

$$= 0 \qquad (4)$$

The "social cost of carbon" in this expression is given by the combination of terms (II) + (III) - (IV). Our interest is in (IV), the marginal external cost of carbon-energy consumption, which, because it emanates from a globally well-mixed pollutant, is independent of the location in which the energy is consumed.

It is now clear to see how fundamental gaps in our understanding the render the "land of cockaigne" unattainable. The difficulty in computing the social cost of carbon stems from the terms in curly braces. Carbon-cycle modeling is sufficiently advanced to enable us to predict with a fair degree of confidence the effect of the marginal ton of carbon on the time-path of future atmospheric GHGs ($\partial \varepsilon / \partial Q^E$). Likewise, the IPCC AR4 notes global climate models' substantially improved ability to capture the future trajectory of consequent changes in temperature, precipitation, ice/snow cover and sea levels at regional scales ($\partial Y_l^m / \partial G$). But the weak links in the causal chain between climate change and economic damages continue to be the cardinality and magnitude of the vectors of physical impact endpoints as a function of climatic variables in each region out into the future ($\partial \varsigma_{j,l}^f / \partial M_l^m$), and—to a lesser extent—the manner in which these endpoints translate into shocks to the productivity of economic sectors ($\partial \lambda_{j,l} / \partial z_{j,l}^f$).

A Critical Review of the State of Modeling Practice

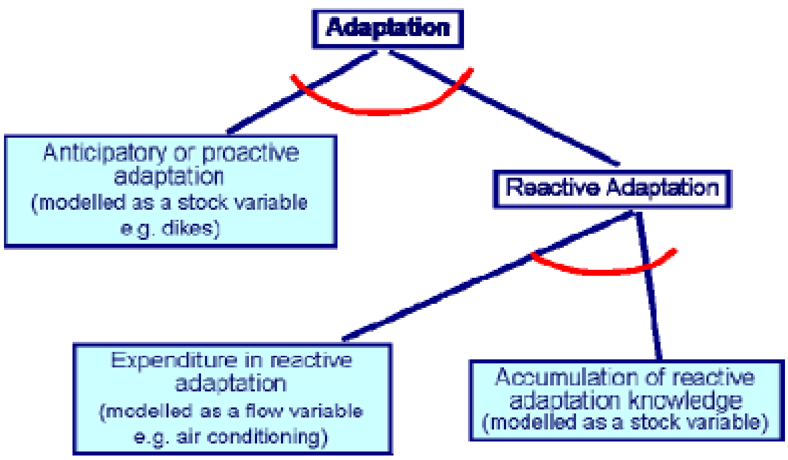
To put the key issues in sharp relief, it is useful to consider how implementing the disaggregated IAM might improve upon the current state of integrated assessment practice. RICE-type IAMs represent the productivity losses incurred by climate change impacts through variants of Nordhaus' aggregate damage function, which specifies the reduction in gross regional product as a function of global mean temperature. This approach effectively collapses M_l^m to a scalar quantity in each time period. Moreover, as reviewed by NRC (2010), it then benchmarks the magnitude of various impacts and the associated economic losses for a reference level of global mean temperature change, before making assumptions about how these costs are likely to scale with income, and finally expressing damage as a temperature-dependent fraction of regions' gross output. Therefore, the details of climatic variables' influence on impact endpoints in (3a), and of the latter's effects on economic sectors in (3b), only affect the calibration of the damage function. From that point on they are entirely subsumed within the function's elasticity with respect to global temperature change, and, in RICE-2010, sea level rise. The damage function therefore collapses (3a) into (3b), dealing only with changes in aggregate global climatic variables, skipping over impacts as state variables and implicitly aggregating over sectors to express damages purely on an aggregate regional basis.

A similar situation obtains with adaptation. A case in point is the AD-WITCH model, a variant of Nordhaus' RICE simulation which modifies the damage function by introducing stock and flow adaptation expenditures which attenuate aggregate regional productivity losses due to climate change. Formally, using eQY to denote gross regional product, net regional product is given by

$$Q^{Y}_{\ell,t} = \frac{1 + ADAPT_{\ell,t}}{1 + ADAPT_{\ell,t} + CCD_{\ell,t}} \widetilde{Q}^{Y}_{\ell,t} \qquad (5)$$

where CCD is the regional climate damage function and ADAPT is an index of adaptation's effectiveness. The variable ADAPT is the output of a nested constant elasticity of substitution (CES) production function which combines inputs of contemporaneous averting expenditures with adaptation capital and adaptation knowledge according to Figure 2. The key consequence is that adaptation is able to directly influence the dynamic path of the economy, instead of being implicit in the curvature of the damage function, as with the RICE model. However, eq. (5)'s assumption that the effects of ADAPT and CCD are multiplicative seems very strong in light of the fact that the damage function already explicitly incorporates the influence of adaptation through the studies on which it is benchmarked—but only at the calibration point, not over the full range of its curvature. A prime example is Nordhaus and Boyer's (2000) use of Yohe and Schlesinger's (1998) results on the impact of sea level rise, which optimally balance the costs of abandonment and coastal defenses. The implication is that because defensive expenditures are likely to be closely associated with the magnitudes of climate impacts of various kinds within individual sectors, one should not think of aggregate adaptation expenditure as independent of future changes in the sectoral composition of output.

Figure 2: The AD-WITCH Adaptation Production Function (Bosello, Carraro and De Cian, 2010)



By dispensing with the aggregate damage function, our land of cockaigne IAM explicitly captures the dynamic evolution of impact endpoints' response to changes in climatic variables, the magnitude and intersectoral distribution of the follow-on productivity effects, and the optimal intersectoral adjustments these induce, all at regional scales. An adaptation response may therefore be modeled more precisely as averting expenditure that mitigates the sectoral and regional productivity loss associated with a particular category of climate impact. In other words, stock and flow adaptation reduces the impact elasticity of sectoral productivity shocks. Of course, the problem that besets this approach is that, except for a very few combinations of impacts, sectors and regions, the relevant elasticities are unknown.

But the good news is that this is one area in which research is proceeding apace. There are a growing number of CGE modeling studies of climate impacts (e.g., ICES) which elucidate the magnitude of both sectoral and regional damages and producers' and consumers' adjustment responses. The focus of such studies is typically a single impact category (say, f*), whose initial economic effects are computed using natural science or engineering modeling or statistical analyses. The results are often expressed as a vector of shocks to exposed sectors and regions, which are then imposed as exogenous productivity declines on the CGE models' cost functions. In the context of the IAM in section 2, this procedure is equivalent to first specifying an exogenous ex-ante effect of a particular impact $\partial\lambda_{j,l} / \partial z_{j,l}^{f^*}$, before using the CGE model to compute the ex-post web of intersectoral adjustments and the consequences for sectoral output, and regions' aggregate net product and welfare:

$$\frac{\partial U_\ell}{\partial Q_{\ell,t}^C} \sum_{j=1}^{\mathcal{N}} \left(\frac{\partial \phi_\ell}{\partial q_{j,\ell,t}^Y} \psi_{j,\ell,t} \overline{\frac{\partial \lambda_{j,\ell}}{\partial z_{j,\ell}^{f^*}}} \right).$$

This line of inquiry has the potential to yield two critical insights. The first is quantification of the elasticity of the economy's response to variations in the magnitude and interregional/ intersectoral distribution of particular types of impact, which has been the type of investigation pursued thus far. But second—and arguably more important—is comparative analysis of economic responses *across* different impact categories for the purpose of establishing their relative overall economic effect, conditional on our limited knowledge of their relative likelihood of occurrence, and intensity. The results could at the very least guide the allocation of effort in investigating the thorny question of how different impacts are likely to respond to climatic forcings at the regional scale, $\partial\varsigma_{j,l}^{f} / \partial M_l^m$.

Adaptation and Technological Change

Karen Fisher-Vanden
Elisa Lanzi
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Mort Webster

The purpose of this talk is to provide a brief summary of the state of the science on the influences of adaptation on the social cost of climate change. Specifically, the charge was to discuss (not necessarily in this order):

(1) relevant studies on the observed or potential effectiveness of adaptive measures, and on private behaviors and public projects regarding adaptation;

(2) relevant studies on how to forecast adaptive capacity;

(3) how adaptation and technical change could be represented in an IAM (for at least one illustrative sector);

(4) whether the information required to calibrate such a model is currently available, and, if not, what new research is needed; and

(5) how well or poorly existing IAMs incorporate the existing body of evidence on adaptation.

A tall order, but important to get our arms around since estimates of the net impact of climate change could be significantly higher if adaptation is not taken into account.[1]

As elaborated below, a number of general insights have resulted from our brief foray into this topic that have implications for the development of a future research program in this area. First, modeling adaptation is inherently difficult given the nature of the adaptation process, requiring advancements in modeling techniques. Second, although there has been good empirical work done on impacts and adaptation costs, the coverage is limited requiring heroic efforts to translate the results into model parameters. More work is needed to bridge the gap between models and empirical studies. Lastly, adaptation-related technological change is generally lacking in current models but could significant lower adaptation cost estimates. This stems from a general lack of understanding of the process related to this type of technological change. More empirical work is needed in this area.

What is unique about the adaptation process that justifies the need to add features to existing integrated assessment models (IAMs)? First, adaptation is in response to current or anticipated impacts and comes in different forms: (a) reactive (e.g., changes in heating/cooling expenditures; treatment of disease; shifts in production); and (b) proactive (e.g., infrastructure construction (e.g., seawalls); early warning systems; water supply protection investments. In some IAMs adaptation

[1] For the U.S., Mendelsohn et al. (1994) estimates that the net impact of climate change on the farming sector will be 70% less if adaptation is included while Yohe et al. (1996) estimates that the net impact on coasts will be approximately 90% less (Mendelsohn (2000)).

would occur endogenously in reaction to changes in prices due to climate impacts—e.g., more power plants built to deal with increases in demand for air conditioning; shifts in production in reaction to higher prices of factors negatively impacted by climate change. However, many adaptation activities that would occur in reality, such as investment in flood protection, would not occur in a simulated model unless there is explicit representation of climate damages to induce reactive expenditures and proactive investments.

Second, unlike mitigation investments where investments today result in reductions today, proactive adaptation investments are made today to provide protection against possible future impacts. Thus, adaptation investment decisions are inherently intertemporal and therefore 2

models need to include intertemporal decision making for proactive adaptation investments, in order to trade off future damages and current adaptation investment expenditures. Not only are we making intertemporal adaptation decisions, we are specifically making proactive adaptation investments under uncertainty. Whether we invest and how much to invest all depends on our expectations regarding future impacts and how we value the future. Therefore, we need a model that allows for intertemporal decision-making under uncertainty.

Climate damages and adaptation strategies are locally- or regionally-based. Therefore, ideally the model will include regional detail or will apply a method to aggregate up to a more coarse regional representation. Climate damages and adaptation expenditures are also sector specific—e.g., certain sectors will be impacted more than others and adaptation expenditures will be directed at specific sectors (e.g., electric power, construction). Thus, a model with sectoral detail or a way to aggregate these sector-specific impacts and expenditures is desirable.

The demand for adaptation solutions will induce adaptation-related technological change. Do inducements for adaptation-related technological change differ markedly from mitigation-related technological change, requiring a different modeling approach? To the extent that adaptation activities may be region or sector specific, markets for new adaptation techniques will be smaller than for new mitigation techniques, making private sector R&D investments less attractive. Given this, as well as the case that adaptation investments are largely public infrastructure investments, distinguishing between public R&D and private R&D may be important. Note that this is more than a question of simply basic versus applied science, but driven by the nature of demand for the final product, much in the same way that the government finances most R&D for national defense. Thus, the model needs to be capable of distinguishing between private and public investments and include mechanisms of public revenue raising to fund these projects.

To summarize, to be able to capture adaptation strategies, an ideal IAM would include the following features:

- Explicit modeling of climate damages/impacts
- Intertemporal decision making under uncertainty
- Endogenous technological change
- Regional and sectoral detail for impacts and adaptation strategies

- Connection with empirical work on impacts and adaptation

Is it feasible or even desirable to have all of these features represented in a single model, since transparency is lost as more features are added? It is important to measure the trade-offs:

- How much of this needs to be specifically represented in the model and how could be represented outside of the model

- To cite Jake Jacoby: ―different horses for different courses.‖ Do we need a suite of models each designed to capture a subset of these features?

- How important is each of these features to the social cost of climate change? Sensitivity analysis could be useful here to assess whether we even need to worry about including certain features.

To answer these questions, it is useful to first survey what features currently exist in IAMs. A number of modeling approaches have been taken to capture impacts and adaptation. Computable general equilibrium (CGE) models have the advantage of providing sectoral and regional detail and capturing the indirect effects of impacts and adaptation. Thus, given its structure, CGE models can more easily accommodate regional and sectoral-specific damage functions. Most CGE models, however, do not include the type of intertemporal decision making required to model proactive adaptation investment decisions, given the computational demands required by a model with detailed regions and sectors. However, there have been a number of CGE models that have been used to estimate the cost of climate change impacts; for example,

- DART (Deke et al, 2001)—to study the cost of coastal protection

- FARM (Darwin and Tol, 2001; Darwin et al, 1995)—includes detailed land types to study the effects of sea level rise and impacts of climate change on agriculture.

- GTAP-E/GTAP-EF (Bosello et al, 2006; Bigano et al, 2008; Rosen, 2003)—has been used to study induced demand for coastal protection; effects of rising temperatures on energy demand (Bosello et al, 2007); health effects of climate change (Bosello et al, 2006); effects of climate change on tourism. Focuses on one impact at a time.

- Hamburg Tourism Model (HTM) (Berittella et al, 2006; Bigano et al, 2008)—used to study the effect of climate change on tourism.

- ICES (Eboli et al, 2010)—models multiple impacts simultaneously: impacts on agriculture, energy demand, human health, tourism, and sea level rise.

Another set of models used to study climate change impacts and adaptation fall under the category of optimal growth models. These models include intertemporal optimization but typically lack sectoral and regional detail given the computational demands this would require. These include:

- DICE/RICE (Nordhaus, 1994; Nordhaus and Yang, 1996; Nordhaus and Boyer, 2000)—DICE comprises one region, one aggregate economy, and one damage function aggregating many impacts. RICE comprises 13 regions, each with its own production function and damage function.

- AD-DICE/AD-RICE (de Bruin et al, 2009)—DICE/RICE model with adaptation. Adaptation investment added as a decision variable which lowers damages and faces an adaptation cost curve. Residual damages are separated from protection costs in the damage function.

There are also a number of simulation models that have been developed to study the effects of climate change impacts. The major difference from CGE and optimal growth models is that simulation models do not optimize an objective function, such as intertemporal utility. Instead, these models represent a number of interconnected relationships that allow for studying the propagation of perturbations to the system. Two widely used simulation models are:

- PAGE (Plambeck and Hope, 1997; Hope, 2006)—PAGE comprises eight regions each with its own damage functions for two impact sectors (economic and non-economic). The authors use information on impacts from IPCC (2001) to generate model parameter values related to impacts. In addition, PAGE stochastically models catastrophic events where the probability of an event increases when temperature exceeds a certain threshold. Simple adaptation is included in the model which reduces damages. Assumes developed countries can reduce up to 90% of economic impacts while developing can reduce up to 50%. All regions can reduce up to 25% of non-economic impacts.

- FUND (Tol et al, 1995; Tol, 1995)—referred to as a —policy optimization|| model. Exogenous variables include population (from the World Bank), GDP per capita (from EMF 14), and energy use. Endogenous variables include atmospheric concentrations, radiative forcing, climate impacts (species loss, agriculture, coastal protection, life loss, tropical cyclones, immigration, emigration, wetland, dryland), emission reductions (energy or carbon efficiency improvements, forestry measures, lower economic output), ancillary benefits (e.g., improved air quality), and afforestation. The model comprises 9 regions with game theoretics and eight market and non-market sectors, each with its own calibrated damage function. Adaptation is modeled explicitly in the agricultural and coastal sectors, and implicitly in other sectors such as energy and human health where the wealthy are assumed to be less vulnerable to the impacts of climate change. No optimization in the base case—just simulation. In the optimization case, the model is choosing the optimal level of emissions reductions by trading off costs and benefits of reductions.

Another class of models involves hybrid combinations of the above model types. For example,

- Bosello and Zhang (2006) couple an optimal growth model with the GTAP-E model of Burniaux and Truong (2002) to study the effects of climate change on agriculture

- Bosello et al (2010) couple the ICES CGE model with an optimal growth model (AD-WITCH) to study adaptation to climate change impacts.

- AD-WITCH (Bosello et al, 2010)—an optimal growth model with detailed bottom-up representation of the energy sector. Comprises 12 regions where the following seven control variables exist for each region: investment in physical capital, investment in R&D, investment in energy technologies, consumption of fossil fuels, investment in proactive adaptation, investment in adaptation knowledge; and reactive adaptation expenditure. These alternative uses of regional income compete with each other.

To parameterize these models, most modeling teams look to empirical studies of impacts and adaptation and are faced with similar frustrations. First, as elaborated in Agrawala and Fankhauser (2008), the empirical work in the area of adaptation is severely lacking. The authors find that although information exists on adaptation costs at the sector level, certain sectors (e.g., coastal zones and agriculture) are studied more heavily than others. Second, most empirical studies are not done with modeling applications in mind. Most modelers find themselves forced to devise methods to scale up from the regional and sectoral results generated by empirical studies.

There have been a few recent studies that have attempted to summarize the empirical work on adaptation costs; e.g.,

- Agrawala and Fankhauser (2008)—provides a critical analysis of empirical work on adaptation costs. Tables summarize empirical sectoral studies on adaptation costs. Sectors include coastal zones, agriculture, water resources, energy demand, infrastructure, tourism and public health.

- World Bank (2010)—report from The Economics of Adaptation to Climate Change (EACC) study. Seven sector-specific studies: infrastructure, coastal zones, water supply and flood protection, agriculture, fisheries, human health, extreme weather events. Provides detailed estimates of adaptation costs; some generated using dose response functions with engineering estimates and some generated from sector-specific models.

- UNFCCC (2007)—regional studies (Africa, Asia, Latin America, and small island developing States) on vulnerability; current adaptation plans/strategies; future adaptation plans/strategies. Most information from national communications to the UNFCCC, regional workshops, and expert meetings.

A few modeling teams have made serious attempts to integrate existing empirical work on adaptation into their model; for example,

- AD-DICE/AD-RICE: starts with damage functions of Nordhaus and Boyer (2000) and uses empirical studies to separate residual damages from adaptation costs. Various studies on adaptation measures for certain sectors (i.e., agriculture and health) and estimates of adaptation costs from existing studies are used. Also, other model results—e.g., results from FUND—are used to estimate adaptation costs in response to sea level rise. Empirical studies to separate residual damages from adaptation costs are not available for many of the sectors—i.e., other vulnerable markets; non-market time use; catastrophic risks; settlements—so assumptions were made in order to separate the damage costs. However, these sectoral estimates are ultimately aggregated up to one damage cost number and one adaptation cost number to fit with the one sector structure of the model.

- AD-WITCH: Uses empirical information from the construction of damage functions in Nordhaus and Boyer (2000), the studies in Agrawala and Fankhauser (2008); and UNFCCC (2007) to separate residual damages from adaptation costs. Similar to AD-DICE, using these empirical studies to separate the damage estimates in Nordhaus and Boyer (2000) into residual damages and adaptation costs.

Comparing this brief survey of existing work in this area with the list of required modeling features needed to model adaptation, a couple of key research voids stand out. First, none of these models include decision making under uncertainty, and for good reason. It is difficult to do. Optimal growth models like DICE with intertemporal decision making are deterministic and fully forward-looking. Past approaches to modify such a model to be stochastic usually entail the following steps:

1) Create multiple States of the World (SOWs), each with different parameter assumptions and different probabilities of occurrence;

2) Index all variables and equations in the model by SOW;

3) Add constraints to the decision variables so that for all time periods before information is revealed, decisions must be equal across SOWs.

The problem with this approach is that it rapidly becomes a very large constrained nonlinear programming problem, and often the model will not converge to a solution for more than a trivial number of SOWs. The general problem of decision making under uncertainty is a stochastic dynamic programming problem that requires the exploration of a large number of samples of outcomes in every time period. The challenge is to fully explore the sample space while keeping the model computationally tractable. Promising on-going research by Mort Webster and his team at MIT could offer an alternative approach to modeling decision making under uncertainty. Webster's NSF-funded project team is currently developing a formulation based a new approach called Approximate Dynamic Programming, introduced by Powell (2007) and others. This approach implements dynamic programming models by iteratively sampling the state space using Monte Carlo techniques, approximating the value function from those samples, and using approximate value functions to solve for an approximate optimal policy, then repeating. This approach has been used successfully in other contexts for very large state spaces. Mort Webster's team is currently developing an ADP version of the ENTICE-BR model to study R&D decision making under uncertainty.

Second, adaptation-related technological change is largely absent in current models. Most models are calibrated using existing knowledge of adaptation strategies and costs with no allowance for improvements in these strategies and technologies. AD-WITCH (Bosello et al, 2009) does attempt to account for this by including investment in adaptation knowledge as a decision variable that competes with other types of investment. Investments in adaptation knowledge accumulate as a stock which reduces the negative impact of climate change on gross output. However, the lack of empirical studies on adaptation-related technological change limits the modelers' ability to calibrate their model based on empirical knowledge. In the case of AD-WITCH, adaptation knowledge investments only relate to R&D expenditures in the health care sector where empirical data exist. This suggests that more empirical research in this area is desperately needed.

Third, differences in adaptive capacity or differences in the ability of regions to adapt to climate change are also important to capture in model analyses given the implications for distributional effects but are typically not represented in existing models. The FUND model implicitly captures adaptive capacity in the energy and health sectors by assuming wealthier nations are less vulnerable to climate impacts. However, it seems that only one model, AD-WITCH, attempts to explicitly capture adaptive capacity through the inclusion of investments in adaptation knowledge as a decision variable. Not only does this variable capture R&D investments in adaptation-related technologies as discussed in the previous paragraph, it also captures expenditures to improve the region's ability to adapt to climate change. Issues arise, however, when the model is calibrated since the modelers were only able to identify one source of qualitative information on adaptive capacity (i.e., the UNFCCC (2007) report discussed above) which only covers four aggregate regions (Africa, Asia, small island developing States, and Latin America). Assumptions were then made to translate this information to the regional representation and model parameters in AD-WITCH.

Lastly, another area where empirical work to inform models is lacking is in the dynamics of recovery from climate change impacts. Most models represent climate damages as a reduction in economic output which is assumed to recover over time. Empirical work on thresholds and time to recover including factors that influence these variables could help inform models on the type of dynamics that should be captured in impact and adaptation analyses. Also, better techniques to translate results from empirical studies to models are needed since the sectoral and regional detail of empirical studies does not typically align with the sectoral and regional detail in models. In general, to address the disconnect between empirical studies and modeling needs, we as a research community need to devise better ways to facilitate communication between empirical researchers and modelers.

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Knowability and no ability in climate projections

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Introduction

The purpose of this note is to provide a referenced summary of the present scientific understanding about future climate change, tailored towards the kind of global climate factors that are captured in Integrated Assessment Models (IAMs). In outline, it is organized as follows:

i) *Equilibrium climate sensitivity* is the long-term response of global temperature to a doubling of atmospheric CO_2. I review the causes of our current uncertainty, and the prospects for reducing it.

ii) Two other measures of climate change are arguably more important in this context. First the *climate commitment* is a measure of the climate change we already face because of emissions that have already occurred.

iii) The very long timescales associated with attaining equilibrium, especially at the high end of possible climate sensitivity, mean that the *transient climate response* is of greater relevance for climate projections over the next several centuries.

iv) Due to the inherent uncertainties in the climate system, a *flexible emissions strategy* is far more effective in avoiding a given level of global temperature change, than a strategy aims to stabilize CO_2 at a particular level.

v) Many important climate impacts are fundamentally regional in nature. Among climate models, regional climate projections correlate only partially with global climate projections.

This was prepared for the EPA Climate Damages Workshop, Washington, D.C., Nov 18-19, 2010.

Climate sensitivity

Climate sensitivity (here given the symbol T_{2x}, and sometimes called the equilibrium climate sensitivity) is the long-term change of annual-mean, globalmean, near-surface air temperature in response to a doubling of carbon dioxide above preindustrial values. It has long been a metric by which to compare different estimates of the climate response to greenhouse gas forcing (e.g., Charney, 1979). There is a vast literature that has researched climate sensitivity from every possible angle, ranging from state-of-the-art satellite observations of Earth's energy budget, to geological studies covering hundreds of millions of years. A fine review of where things stand can be found in Knutti and Hegerl (2008).

Figure 1 shows a variety of probability distributions (pdfs) of climate sensitivity. A prominent feature of such estimates is that they all exhibit considerable skewness. In other words, while the lower bound is confidently known, the upper bound is much more poorly constrained. There is a small but nontrivial possibility (about 25 %) that the climate sensitivity could exceed 4.5 ^oC. One concern that has been raised is that the current generation of IPCC climate models (from the fourth assessment, or AR4) does not span the range of climate sensitivity that is allowable by observations (the blue histogram in figure 1 clusters too narrowly around the modes of the other pdfs). The reason for this appears to be that the IPCC climate models do not sample the full range of possible aerosol forcing (Armor and Roe, 2010). This should not be surprising since they are designed to represent the "best" estimate of climate (something akin to the mode of the distribution). However, since these computer models are the only tools available for modeling regional climates, it should perhaps be a concern that they are under sampling the range of possible futures. I next outline briefly how estimates are made from observations and models. The purpose of doing so is to straightforwardly demonstrate the important sources of uncertainty.

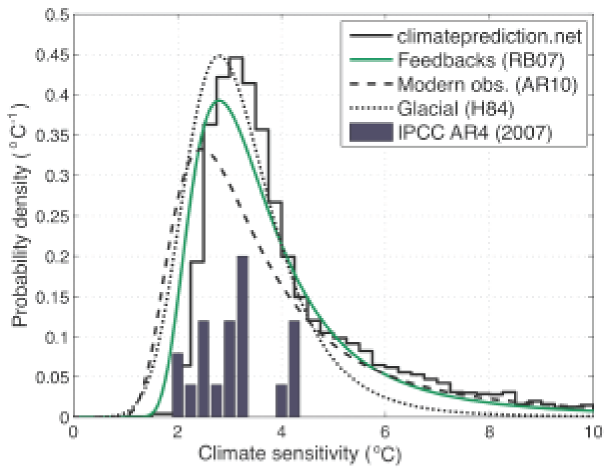

Figure 1. Various estimates of climate sensitivity. In order of the legend: i) from multi-thousand ensembles from one climate model (Stainforth et al., 2005), ii) from feedbacks with climate models (Roe and Baker, 2007), iii) from modern observations (Armour and Roe, 2010), iv) from glacial climates (Hansen et al., 1984), v) A histogram of T_{2x} from 19 main IPCC AR4 models (IPCC, 2007).

Estimates of climate sensitivity from observations.

A linear approximation of the Earth's energy budget is:

$$\mathbf{R = H + \lambda^{-1}T,} \qquad \textbf{(1)}$$

where *R* is the radiative forcing (units W m^{-2}), *H* is the heat going into the world's oceans and being stored there, and $\lambda^{-1}T$ is the climate response in terms of the global-mean, annual-mean, near-surface air temperature *T*, and the climate sensitivity parameter, λ. (e.g., Roe, 2009, Armour and Roe, 2010, and many others). For silly historical reasons the terminology here can be confusing. λ is a more fundamental measure of climate system than T_{2x}, since it does not depend on any particular forcing. λ and T_{2x} are related in the following way. Let R_{2x} be the radiative forcing due to a doubling of CO_2 over pre-industrial values (≈ 4 W m-2). In the long-term equilibrium, ocean heat uptake goes to zero, and so the climate sensitivity is just:

$$T_{2x} = \lambda R_{2x} \qquad \textbf{(2)}$$

The point of this algebra is to make it clear that the goal of estimating climate sensitivity from observations is the goal of estimating λ from Equation (1):

$$\lambda = \frac{T}{R - H} \qquad \textbf{(3)}$$

We have observations of *T*, *R,* and *H*, whose probability distributions are shown in figure 2. Hereafter we refer to *R*-*H* as the climate forcing, since it is the net energy imbalance that the atmosphere must deal with. *H* and *T* are actually quite well constrained, as is the radiative forcing associated with CO_2 and other greenhouse gases. As is clear from figure, the major source of uncertainty is *R* and, in particular, the component of R that is due to aerosols (small airborne particulates that can be either liquid or solid).

The reason that aerosol forcing is hard to constrain is that 1) the spatial pattern and lifetime is extremely complicated to observe (they are primarily in the Northern Hemisphere and downwind of major industrial economies); 2) some aerosols have a cooling effect, some have a warming effect; 3) aerosols alter the thickness, lifetime, and height of clouds – a powerful indirect effect that is hard to measure and attribute properly. The community is confident, however, that the net aerosol effect is almost certainly negative. More information about aerosol uncertainties can be found in Menon (2004).

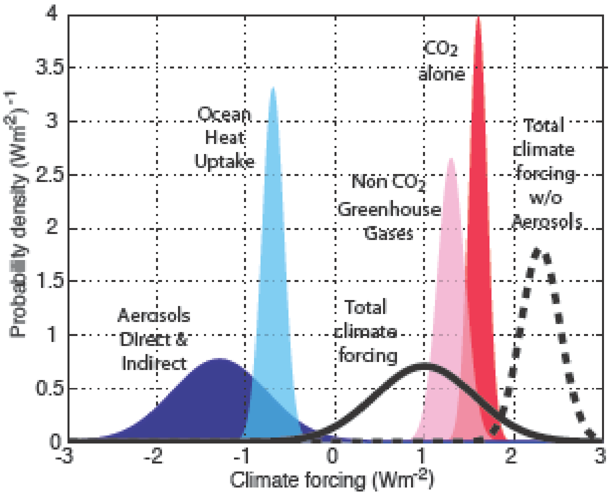

Figure 2: Probability distributions of the terms in the Earth's energy budget, based on IPCC 2007, and updated for newer ocean heat uptake observations. See Armour and Roe, 2010 for details. Total climate forcing is equal to R-H in Eq. 3. Also shown is the total forcing excluding aerosols, which is the climate forcing experienced by the Earth, if all anthropogenic emissions ceased immediately.

Thus, from Eqs. 2 and 3, the probability distribution of climate sensitivity comes from combining a relatively narrow distribution (the well-known temperature change) in the numerator with a relatively broad distribution (the much less wellknown climate forcing (i.e., R-H)) in the denominator of Eq. 3. It is this combination that produces the skewed distribution seen in figures 1 and 3c. The graphs in figure 3 are the fundamental reason why we can say with great confidence that it is very likely that observed forcing has not been large enough to imply a climate sensitivity of less than about 1.5 oC. On the other hand, uncertainties in observed forcing also mean that we cannot confidently rule out the disconcerting possibility that the modern warming has occurred with small climate forcing, which would imply very high climate sensitivity. Note that the curves in figure 1 and 3 are consistent with the probabilities given in the 2007 IPCC report.

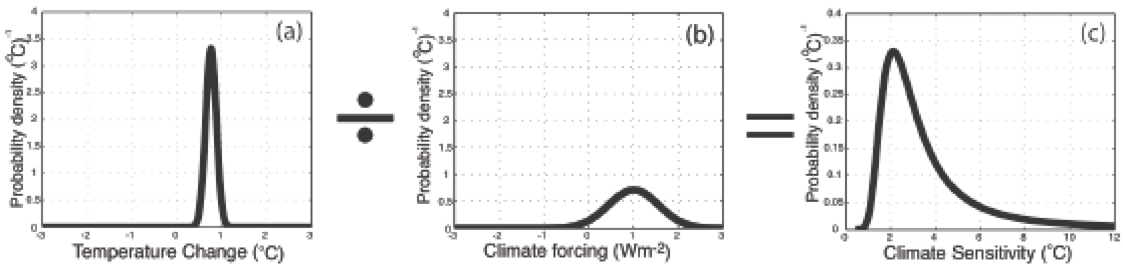

Figure 3: The calculation of climate sensitivity from observations involves combing a relatively narrow probability distribution of T (panel a) in the numerator, with a relatively broad distribution of F= H-R (panel b) in the denominator of Eq. (3). This leads to the skewed distribution of climate sensitivity (panel c). Note the pdfs must be combined properly - it is not just a simple division - but the point is hopefully clear.

Estimates of climate sensitivity from models.

Climate sensitivity also can be estimated from climate models. Figure 1 shows three such efforts. The first is the spread of T_{2x} among the main IPCC AR4 models. One issue is that the mainstream IPCC AR4 climate models are not designed to explore the edges of the probability distribution, but instead are designed with the most likely combination of model parameters, and parameters are 'tuned' to reproduce observed climate history. Clear evidence of that tuning comes from the correlation of climate sensitivity and imposed aerosol forcing in the models in such a direction that twentieth century observations tend to be reproduced (Kiehl, 2007, Knutti, 2008). Such tuning is not problematic if models are interpreted as reflecting combinations of climate sensitivity and aerosol forcing that are consistent with observed constraints (Knutti, 2008). However AR4 models do not fully span the range of aerosol forcing allowed by observations (Kiehl, 2007; IPCC, 2007). This is the likely reason that the AR4 models under sample of the full range of possible climate sensitivity, as seen in figure 1.

Climate sensitivity can also be estimated by using thousands of integrations of the same climate model with the parameters varied by reasonable amounts, a strategy pursued by the climateprediction.net effort (figure 1, e.g., Stainforth et al., 2005). This work also found a skewed pdf of T2x. Roe and Baker (2007) explain this in terms of a classic feedback analysis, summarized in figure 4. The relationship between feedbacks and response also produces a skewed distribution because of the way that positive feedbacks have a compounding effect on each other (e.g., Roe, 2009). The range of feedbacks as diagnosed within the AR4 models produces a pdf of climate sensitivity that is quite consistent with the pdf estimated from observations (figure 1). This should be expected since it is observations that ultimately provide constraints on the models.

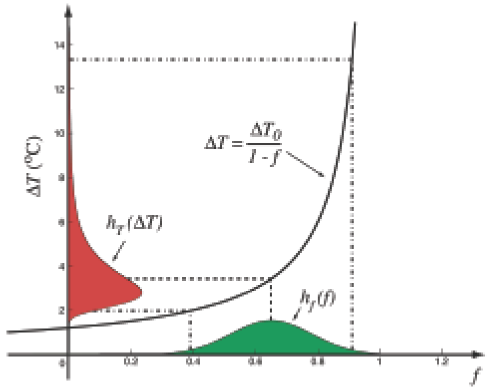

Figure 4: Model feedbacks and climate sensitivity. The black curve shows the mapping between climate feedbacks (x-axis, green curve), and climate response (y-axis, red curve). See Roe and Baker, 2007 for details.

Prospects for improved estimates of climate sensitivity.

Can a narrower range of climate sensitivity be expected soon? One can ask: how might more accurate observations or better climate models change the estimate of T_{2x}?

Reducing uncertainty in either forcing or feedbacks would produce a narrower range. However it is the nature of these skewed distributions that the mode of T_{2x} moves to higher values as the range of forcing or feedbacks is narrowed, leaving the cumulative probability of $T_{2x} > 4.5°C$ stubbornly persistent (Allen et al., 2007; Roe and Baker, 2007; Baker et al., 2010).

It should also be made clear that there are formidable scientific challenges in reducing uncertainty in climate model feedbacks, or in observing the aerosol forcing better. Progress will occur, but it is likely that it will be incremental. Another line of attack is to try to combine multiple estimates of climate sensitivity in a Bayesian approach that might, in principal, significantly slim the fat tail of T_{2x} (e.g., Annan and Hargreaves, 2006). However, as with all Bayesian estimates, the value of the analysis is critically sensitive to 1) the independence of different observations; and 2) structural uncertainties within and among very complex models (e.g., Henriksson et al., 2010; Knutti et al., 2010). An objective assessment of these factors has proven elusive, rendering the information obtained by the exercise hard to interpret, and there is an acute risk that it produces overconfident estimates.

Overall it is probably prudent to anticipate that there will not be dramatic reductions in uncertainty about the upper bound on climate sensitivity (Knutti and Hegerl, 2008). On the timescale of several decades, Nature herself will slowly reveal more of the answer. We will learn about the transient climate response (see below) more quickly than the equilibrium climate sensitivity. Those interested in understanding the above arguments in greater depth would do well to read the work of Prof. Reto Knutti (at ETH in Switzerland) and his collaborators. His research is of extremely high caliber, and quite accessible for a non-specialist.

The climate commitment.

What if all human influence on climate ceased overnight? Such a scenario— called the *climate commitment*—informs us of the climate change we already face due only to past greenhouse gas emissions. Framing the question this way has proven to be useful in providing a conceptual lower bound on future climate warming.

Early definitions of the climate commitment simply fixed CO_2 concentrations at current levels (e.g., Wigley, 2005; Meehl et al., 2005), but maintaining current levels actually requires continued emissions. Lately the focus has been more appropriately on the consequences of establishing zero emissions (e.g., Solomon et al., 2009). Two important, though sometimes overlooked points should be made. Firstly the geological carbon cycle means that, although much of the anthropogenic CO2 ultimately gets absorbed by the ocean, some fraction — about 25 to 40% — remains in the atmosphere for hundreds of thousands of years (e.g., Archer et al., 2009). Secondly aerosols, have a short lifetime in the atmosphere (days to weeks). Thus when human influence ceases, aerosols are rapidly washed out of the atmosphere and the effect of this is to unmask additional warming due to

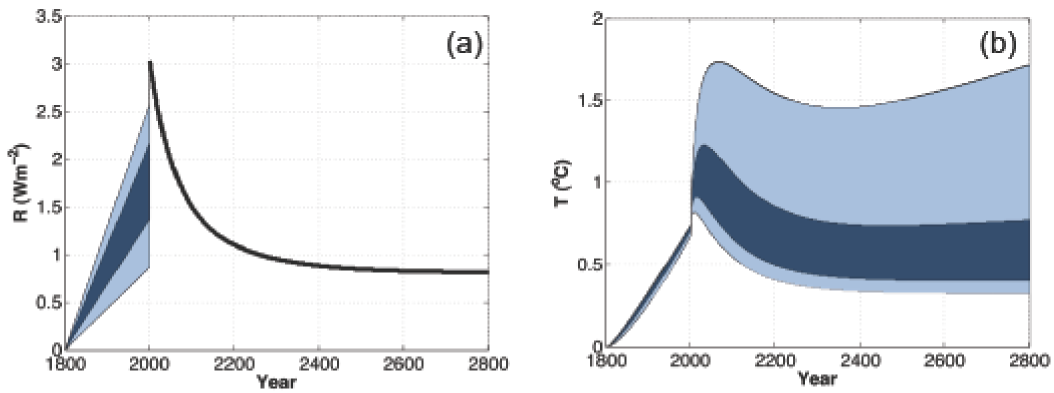

Figure 5: Idealized representation of the climate commitment following a cessation of all human influence on climate. Based on Armour and Roe, 2010. Panel (a) shows a simple view of how uncertainty in forcing has grown since 1800, as allowed by IPCC 2007 observed uncertainties. After emission cease (here at yr 2000) the uncertain aerosols quickly vanish, there is a jump in forcing due to sudden unmasking of the (relatively well-known) radiative forcing due to CO_2 and other greenhouse gases, which then declines slowly over time (black line). Panel (b) shows the temperature over this period, from a simple climate model. For each possible trajectory of past climate forcing history, a different value of climate sensitivity is implied, in order that the accurately known past warming is reproduced (low past forcing requires high climate sensitivity, and vice versa). The light blue curve shows the 90% confidence range, as permitted by uncertainties in observations, which ultimately grows to be 0.3 to 6°C at equilibrium. The dark blue curve is the `likely' IPCC range (68%). It is this range that is spanned by the main IPCC AR4 models because they under sample the allowed range of past forcing. Note that these calculations here only include uncertainties due to aerosols. The spread would be larger if uncertainties in GHG and ocean heat uptake were included. Nonetheless the graph highlights that uncertainty in future temperatures is a result of uncertainty in past forcing.

the much more slowly declining CO2 (illustrated in figure 2 and 5).

Figure 5 shows an idealized calculation of the climate commitment from Armour and Roe (2010), which contains more details. The purpose of showing this is to highlight that our uncertainty about future temperature comes primarily from our uncertainty about past forcing. After ceasing all emissions, the degree and trajectory of future warming depends on the state of the current climate forcing. We face the disconcerting possibility that our ultimate climate commitment already exceeds 2 °C, because of our current inability to rule out that past warming occurred with relatively little climate forcing. In other words, the lower flank of the pdf of the past climate forcing distribution (figure 5a) controls the upper flank of the pdf of the future temperature response (figure 5b).

Climate forcing and climate sensitivity are not independent.

Perhaps the most important point to emphasize for the application to integrated assessment models (IAMs) is that climate sensitivity and climate forcing are not independent of each other. For any projections made of the future, a starting point for the current climate forcing must be assumed. We are currently quite uncertain about what that starting point is. If aerosol forcing is strongly negative, there is a strong implication that climate sensitivity is high. If aerosol forcing is weak, climate sensitivity must be low. Uncertainties in climate forcing and climate sensitivity must not be assumed to be independent.

The transient climate response.

Equilibrium climate sensitivity relates to a hypothetical distant future climate after the system has equilibrated to a stipulated forcing. The transient climate response over the course of a few centuries may be a more directly useful property of the climate system. A formal definition of the transient climate sensitivity has been proposed as the global-average surface air temperature, averaged over the 20-year period centered on the time of CO_2 doubling in a 1% yr^{-1} increase experiment, which occurs roughly at 2070. While this metric may be more relevant for the future, a negative trade-off is that its exact value depends on this artificially defined trajectory of emissions.

For reasons discussed below, the transient climate response is much better constrained than climate sensitivity. In the words of the IPCC, it is very likely (> 9- in-10) to be greater than 1°C and very unlikely (< 1-in-10) to be greater than 3 °C. Thus the community is much more confident about the evolution of the climate over the coming century than it is about the ultimate warming.

The immensely long timescales of high sensitivity climates.

A key factor in the long-term evolution of the climate is the diffusive nature of the ocean heat storage (figure 6b). In order to reach equilibrium the ocean abyss must also warm, and because of the relatively sluggish circulation of the deep ocean, the upper layers must be warmed before the lower layers, and the more the temperature change must be, the longer diffusion takes to work. A simple scaling analysis (e.g., Hansen et al., 1985) shows that:

$$\text{Climate adjustment time } \alpha \text{ (climate sensitivity)}^2$$

Thus if it takes 50 yrs to equilibrate with a climate sensitivity of 1.5 °C, it would take 100 times longer, or 5,000 yrs to equilibrate if the climate sensitivity is 15 °C. Although Nature is of course more complicated than this, the basic picture is reproduced in models with an (albeit simplified) ocean circulation. Figure 6a shows one such calculation from Baker and Roe (2009), though there are others (in particular see Held et al., 2010).

If IAMs are to be used to project out more than a few decades, it is critical that they represent this physics correctly. A single adjustment time for climate, or a deep ocean that is represented as a uniform block, cannot represent this behavior.

The extremely high temperatures found in the fat tail of climate sensitivity cannot be reached for many centuries for very robust physical reasons. Failure to incorporate this fact will lead to a strong distortion of the evolution of possible climate states, and of the subsequent IAM analyses based on them.

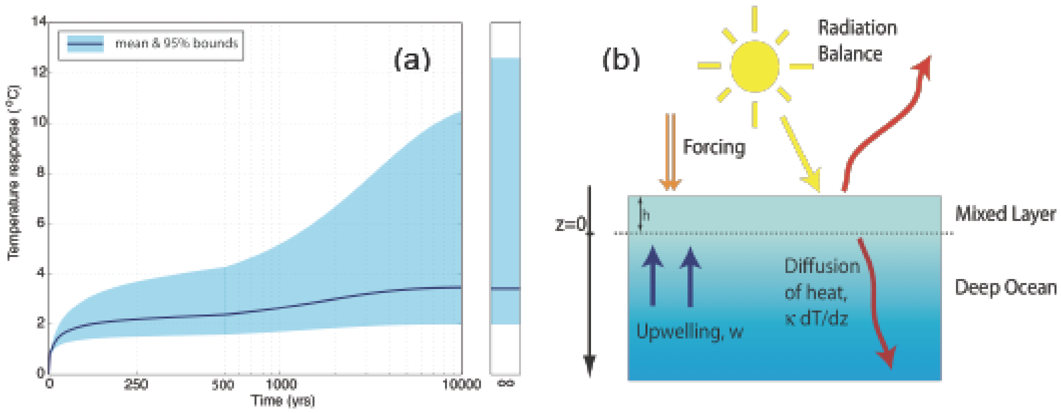

Figure 6: (a) The evolution of possible climate trajectories in response to an instantaneous doubling of CO_2 given the existing uncertainty in climate sensitivity. From Baker and Roe, 2009. Note the change to a logarithmic x-axis after 500 years. Low climate sensitivity is associated with rapid adjustment times (decades to a century). High climate sensitivity has extremely long adjustment times – thousand of years. This results from the fundamentally diffusive nature of the ocean heat uptake, illustrated schematically in panel (b). Such behavior is also reproduced in more complete physical models. See Held et al. (2010), for example.

CO_2 stabilization targets are a mistake.

A prominent part of the conversation about action on climate change has centered on what the right level of CO_2 should be in the atmosphere (e.g., Solomon et al., 2010). Some advocate for 350 ppmv (e.g., Hansen et al. 2008), though we are already past 380 ppmv and climbing, others contemplate the consequences of 450 ppmv (e.g., Hansen, et al., 2007), still others 550 ppmv (Pacala and Soccolov, 2004; Stern, 2007).

However decreeing and setting in stone a particular target for CO_2 is fundamentally the wrong approach, and a vastly inefficient way to avoid a particular climate scenario. This point was made very elegantly and powerfully in a study by Allen and Frame (2007), reproduced in figure 7. Panel a) shows a scenario of what could happen if we decided today to stabilize CO_2 at 450 ppmv by 2100,

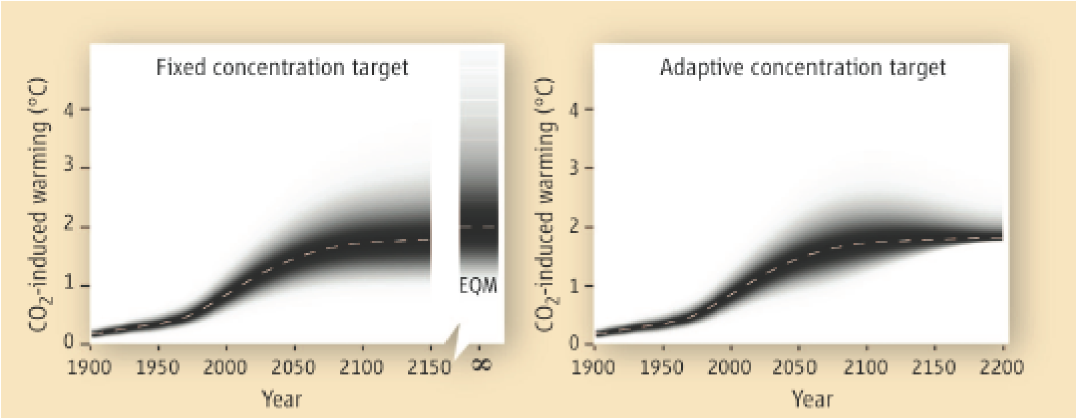

Figure 7: reproduced from Allen and Frame (2007). Carbon dioxide–induced warming under two scenarios simulated by an ensemble of simple climate models. (Left) CO_2 levels are stabilized in 2100 at 450 ppm; (right) the stabilization target is recomputed in 2050. Shading denotes the likelihood of a particular simulation based on goodness-of-fit to observations of recent surface and subsurface-ocean temperature trends. The darker the shading, the likelier the outcome.

and then waited for the climate to evolve. Our current best guess is that would lead to an equilibrium temperature change of 2 °C, taking us to the edge of what some have called dangerous climate change. However because of our current uncertainty in climate sensitivity, the envelope of possible climate states is quite broad by 2150. In other words, our hypothetical choice that we made today still leaves us exposed to a quite broad envelope of risk. Note, though, that figure 7a is consistent with figure 6 – temperatures in the fat tail of high climate sensitivity are still very, very far from equilibrium at 2150.

Panel b) of figure 7 considers an alternative strategy in which we still act according to our best guess today, but re-compute a new concentration target at 2050, based on the fact that 40 years have elapsed and Nature has given us more information about what trajectory we are on. Figure 7b makes it clear that this adaptive strategy is vastly more effective in achieving a desired climate target (in this case a global temperature change of 2 °C). Because the link between CO_2 levels and global temperature is uncertain, and because it is prudent to anticipate only incremental advances in our understanding, it is common sense to pursue a strategy that has built-in flexibility rather than declaring a fixed concentration.

How well do global projections correspond to regional projections?

Many of the most important climate impacts – changes in hydrology, storminess, heat waves, snowpack, etc. – are fundamentally regional in nature. How reliable is global climate change as a predictor of regional climate change? Since this is a question about the future, we are forced to use climate models. Figure 8 analyzes how well global climate sensitivity correlates with local climate change (in this case annual mean temperature and precipitation change in 2100), comparing among eighteen different IPCC models (IPCC, 2007).

It takes a correlation of r ~ 0.75 before half of the variance (i.e., r^2) of the local climate change is attributable to the global climate change. Only a very few patches of the planet achieve even this level of correlation in annual temperature (Figure 8a) and nowhere reaches this measure in annual precipitation (Figure 8b). This highlights that the connection between regional and global climate change is not that strong. This result should not be surprising: though models may all agree on the *sign* of the climate change in a given region, there is a great deal of scatter and individual model vagaries in projecting the *magnitude* of the climate change. Research into the limits of regional predictability is only just beginning. A useful starting point is Hawkins and Sutton (2009).

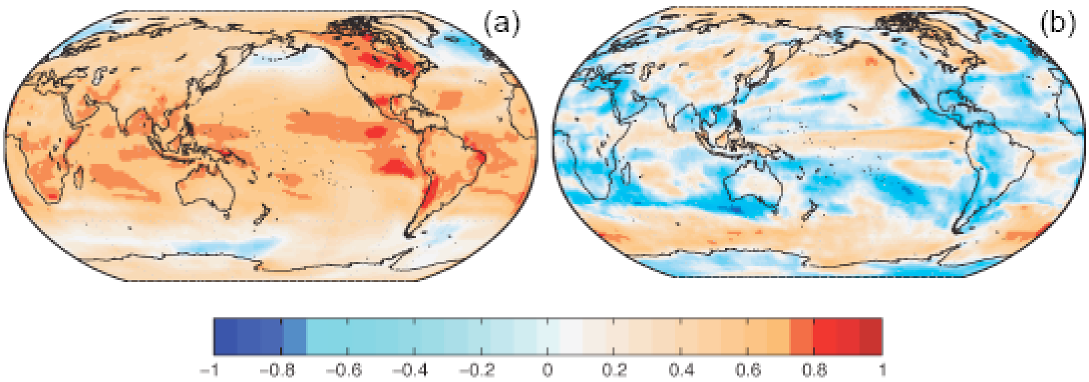

Figure 8: a) correlation among 17 IPCC climate models of their global equilibrium climate sensitivity and their local annual-mean temperature change in 2100,; b) same as a), but for annual-mean precipitation. Calculation made by N. Feldl from IPCC archived model output based on the A1B emissions scenario, and similar plots for other variables are at *http://earthweb.ess.washington.edu/roe/GerardWeb/Publications.html*.

Summary.

1) The most important point to drive home is that uncertainty is not ignorance. The planet has warmed in the recent past, and will continue to warm for the foreseeable future. That this is a result of our actions is beyond rational dispute. The overwhelming preponderance of the IPCC 2007 report is extremely reliable, and reflects an objective characterization of the best current understanding about climate. All of the following points are consistent with (and in many cases drawn from) that report.

2) A traditional measure of the planet's response, equilibrium climate sensitivity is uncertain, primarily because of uncertainty in the radiative forcing due to aerosols. This precludes us from calibrating our models of climate with greater accuracy.

3) However a focus on climate sensitivity may be misplaced because of the tremendously long timescales associated with reaching equilibrium – thousands of years in the case of the fat tail of high climate sensitivity.

4) If all human influence were to cease today, the rapid loss of anthropogenic aerosols from the climate would unmask CO_2 warming, and the planet's temperature would increase as a result. The degree of warming is quite uncertain.

5) For related reasons, a strategy that aims to stabilize concentration of greenhouse gasses at a particular level is a mistake, because the degree of warming is still unpredictable. A strategy that aims for a flexible emissions will be much more effective at preventing a particular level of warming.

6) IAMs have to make choices about how to represent climate forcing associated with human activity. We are quite uncertain about what this level is right now. It is crucial to appreciate that uncertainty in climate sensitivity and uncertainty in climate forcing cannot be treated as independent.

7) Many climate damages both to humans and to the biosphere result from regional climate factors. Unfortunately, there is relatively little agreement among climate models about how global climate changes relate to local climate changes, and this is especially true in some of the most vulnerable subtropical regions. Thus the meaning of analyses that use only global temperature changes to assign climate damages is unclear.

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Notes for EPA & DOE discussion meeting

Martin L. Weitzman
November, 2010

First thoughts on "'thinking about' high-temperature damages from potential catastrophes in climate change."

'Thinking about' is the right phrase. This is a notoriously intractable area even to conceptualize, much less to model or to quantify. Don't expect miracles or breakthroughs here — too many "unknown unknowns" with seemingly non-negligible probabilities to feel comfortable with.

What is the nature of the beast?

The economics of climate change consists of a very long chain of tenuous inferences fraught with big uncertainties in every link: beginning with unknown base-case GHG emissions; then compounded by big uncertainties about how available policies and policy levers will transfer into actual GHG emissions; compounded by big uncertainties about how GHG flow emissions accumulate via the carbon cycle into GHG stock concentrations; compounded by big uncertainties about how and when GHG stock concentrations translate into global average temperature changes; compounded by big uncertainties about how global average temperature changes decompose into regional climate changes; compounded by big uncertainties about how adaptations to, and mitigations of, regional climate-change damages are translated into regional utility changes via a regional "damages function"; compounded by big uncertainties about how future regional utility changes are aggregated into a worldwide utility function and what should be its overall degree of risk aversion; compounded by big uncertainties about what discount rate should be used to convert everything into expected-present-discounted values. The result of this lengthy cascading of big uncertainties is a reduced form of truly enormous uncertainty about an integrated assessment problem whose structure wants badly be transparently understood and stress tested for catastrophic outcomes.

Let welfare W stand for expected present discounted utility, whose theoretical upper bound is B. Let $D \equiv B - W$ be expected present discounted disutility. Here D stands for what might be called the "diswelfare" of climate change. Unless otherwise noted, my default meaning of the term "fat tail" (or "thin tail") will concern the upper tail of the PDF of lnD, resulting from whatever combination of probabilistic temperature changes, temperature-sensitive damages, discounting, and so forth, by which this comes about. Empirically, it is not the fatness of the tail of temperature PDFs *alone* or the reactivity of the damages function to high temperatures *alone*, or any other factor *alone*, that counts, but the *combination* of all such factors. Probability of welfare-loss catastrophe declines in impact size, but key question here is: *how fast* a decline relative to size of catastrophe? When we turn to theory, it seems to highlight that the core "tail fattening" mechanism is an inherent inability to learn about extreme events from limited data.

What do rough calculations show about this beast?

I have played with some extremely rough numerical examples. GHG concentration implies a PDF of temperature responses implies a PDF of damages (given a "damages function"). In order to get tail fatness to matter for willingness to pay to avoid climate change requires a *much* more reactive damages function than the usual quadratic. Usual quadratic damages function loses 26% of output for a 12dC temperature change. At 2% annual growth rate, 12dC change 200 years from now implies that welfare-equivalent consumption then will still be *37 times higher than today*. If you use the standard quadratic damages function, you cannot get much damage from extreme temperatures. If make a reactive damages function, such that, say, 12dC temperature increase causes welfare-equivalent consumption to shrink to, say, 5% of today's level, then get very high WTP to reduce GHG target levels. Model is terrified of flirting with high CO2-e levels, especially above 700 ppm. Incredible dependence on degree of risk aversion (2, 3, or 4?), fatness of tail PDFs (climate sensitivity PDF: normal, lognormal, Pareto?), and so forth. My own tentative summary conclusion: tail of extreme climate change welfare-loss possibilities is much too fat for comfort when combined with reactive damages at high temperatures. It looks like this could influence such things as social cost of carbon.

Is there anything constructive to take away from this gloomy beast?

My tentative answer: a qualified maybe. Some possible rough ideas follow.

1. Keep a sense of balance. A small but fat-tailed probability of disastrous damages is not a realization of a disaster. Highly likely outcome is a future sense that we dodged a bullet (like Cuban missile crisis?). Yet when all is said and done, catastrophic climate change looks to me like a very serious issue.

2. Try standard CBA or IAM exercises in good faith. *But*, be prepared – when dealing with extremes – that answers might depend non-robustly upon seemingly-obscure assumptions about tail fatness, about how the extreme damages are specified (functional forms, parameter values, etc.), assumptions about rates of pure time preference, degrees of risk aversion, Bayesian learning, CO2 stock inertia, CH4 releases from clathrates, mid-course correction possibilities, etc. Some crude calculations seem to indicate great welfare sensitivity to seemingly-obscure factors such as the above, most of which are difficult to know with any degree of precision. Do CBAs and IAMs, study answers, but maybe don't try to deny the undeniable if these answers are sensitive to tail assumptions in a highly nonlinear welfare response to extreme uncertainty.

3. Should we admit to the public that climate change CBA looks more iffy and less robust than, say, CBA of SO2 abatement, or would this be self defeating?

4. Maybe there should be relatively more research emphasis on understanding extreme tail behavior of climate-change welfare disasters. Alas, this is very easy to say but very difficult to enact. How do we learn the fatness of PDF tails from limited observations or experience?

5. A need to compare how fat are tails of climate-change welfare loss with how fat are tails of any proposed solutions, such as nuclear power, below-ground carbon sequestration, etc.

6. Suppose that a lot of expected present discounted disutility is in the bad fat tail of the welfare-loss PDF. Realistically, how can we limit some of the most horrific losses in worst-case scenarios? Can we filter-learn fast enough to offset residence time of atmospheric CO2 stocks by altering GHG emission flows in time to work? Is tail fatness an argument for developing an emergency-standby backstop role for fast geoengineering? Any other backstop options? Take-home lesson here: hope for the best and prepare for the worst. At least we should be prepared, beforehand, for dealing with ugly scenarios, even if they are low-probability events. Should the discussion about emergency preparedness begin now?

Earth System Tipping Points

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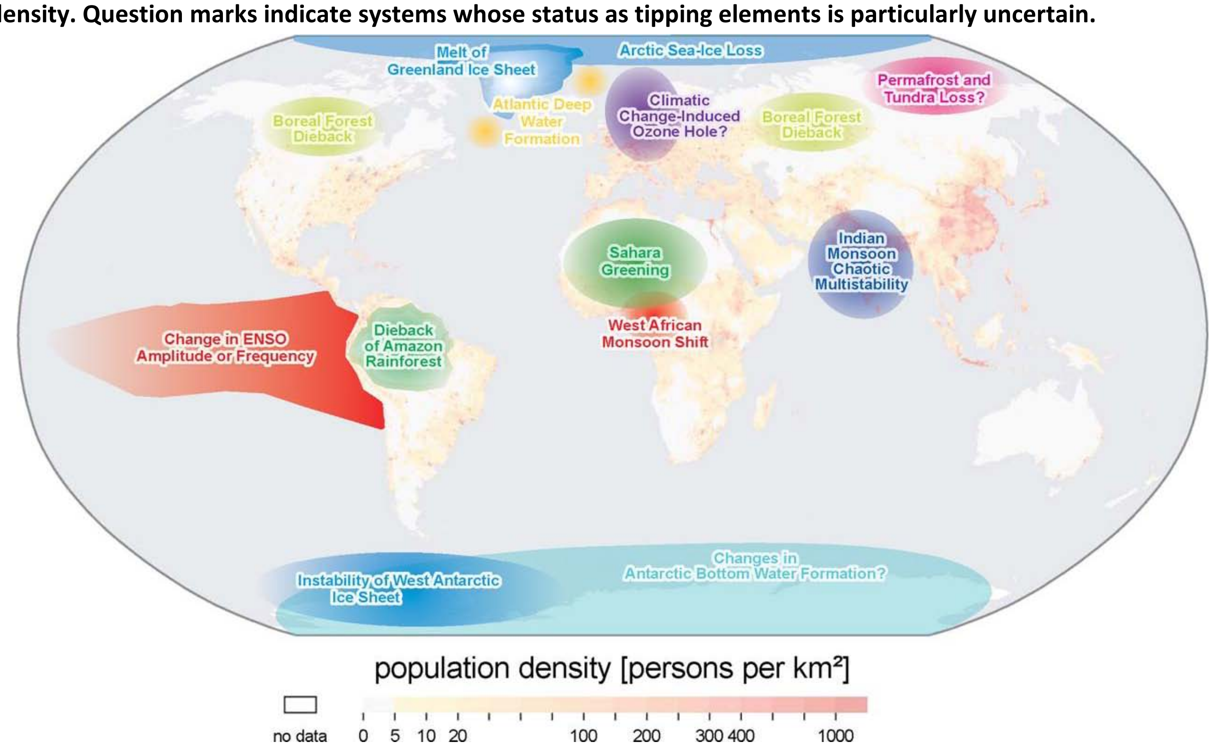
Definitions

A **tipping point** is a critical threshold at which the future state of a system can be qualitatively altered by a small change in forcing[1]. A **tipping element** is a part of the Earth system (at least sub-continental in scale) that has a tipping point[1]. Policy-relevant tipping elements are those that could be forced past a tipping point this century by human activities. **Abrupt climate change** is the subset of tipping point change which occurs faster than its cause[2]. Tipping point change also includes transitions that are slower than their cause (in both cases the rate is determined by the system itself). In either case the change in state may be reversible or irreversible. **Reversible** means that when the forcing is returned below the tipping point the system recovers its original state (either abruptly or gradually). **Irreversible** means that it does not (it takes a larger change in forcing to recover). Reversibility in principle does not mean that changes will be reversible in practice.

Tipping elements in the Earth's climate system

Previous work[1] identified a shortlist of nine potential policy-relevant tipping elements in the climate system that could pass a tipping point this century and undergo a transition this millennium under projected climate change. These are shown with some other candidates in Figure 1.

Figure 1: Map of potential policy-relevant tipping elements in the Earth's climate system overlain on population density. Question marks indicate systems whose status as tipping elements is particularly uncertain.



We should be most concerned about those tipping points that are nearest (least avoidable) and those that have the largest negative impacts. Generally, the more rapid and less reversible a transition is, the greater its impacts. Additionally, any positive feedback to global climate change may increase concern, as can interactions whereby tipping one element encourages tipping another. The proximity of some tipping points has been assessed through expert elicitation[1,3]. Proximity, rate and reversibility have been also assessed through literature review[1], but there is a need for more detailed consideration of impacts[4]. The following are some of the most concerning tipping elements:

The **Greenland ice sheet** (GIS) may be nearing a tipping point where it is committed to shrink[1,3]. Striking amplification of seasonal melt was observed in summer 2007 associated with record Arctic sea-ice loss[5]. Once underway the transition to a smaller ice cap will have low reversibility, although it is likely to take several centuries (and is therefore not abrupt). The impacts via sea level rise will ultimately be large and global, but will depend on the rate of ice sheet shrinkage. Latest work suggests there may be several stable states for ice volume, with the first transition involving retreat of the ice sheet onto land and around 1.5 m of sea level rise[6].

The **West Antarctic ice sheet** (WAIS) is currently assessed to be further from a tipping point than the GIS, but this is more uncertain[1,3]. Recent work has shown that multiple stable states can exist for the grounding line of the WAIS, and that it has collapsed repeatedly in the past. It has the potential for more rapid change and hence greater impacts than the GIS.

The **Amazon rainforest** experienced widespread drought in 2005 turning the region from a sink to a source (0.6-0.8 PgC yr^{-1}) of carbon[7]. If anthropogenic-forced[8] lengthening of the dry season continues, and droughts increase in frequency or severity[9], the rainforest could reach a tipping point resulting in dieback of up to ~80% of the rainforest[10-13], and its replacement by savannah. This could take a few decades, would have low reversibility, large regional impacts, and knock-on effects far away. Widespread dieback is expected in a >4 °C warmer world[3], and it could be committed to at a lower global temperature, long before it begins to be observed[14].

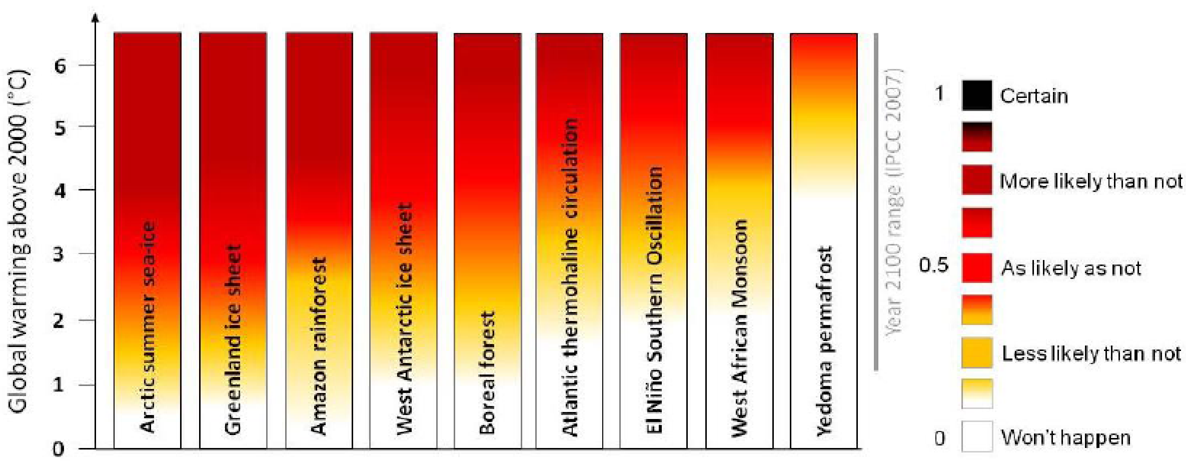
The **Sahel and West African Monsoon** (WAM) have experienced rapid but reversible changes in the past, including devastating drought from the late 1960s through the 1980s. Forecast future weakening of the Atlantic thermohaline circulation contributing to 'Atlantic Niño' conditions, including strong warming in the Gulf of Guinea[15], could disrupt the seasonal onset of the WAM16 and its later 'jump' northwards[17] into the Sahel. Whilst this might be expected to dry the Sahel, current global models give conflicting results. In one, if the WAM circulation collapses, this leads to wetting of parts of the Sahel as moist air is drawn in from the Atlantic to the West[15,18], greening the region in what would be a rare example of a positive tipping point.

The **Indian Summer Monsoon** (ISM) is probably already being disrupted[19,20] by an atmospheric brown cloud (ABC) haze that sits over the sub-continent and, to a lesser degree, the Indian Ocean. The ABC haze is comprised of a mixture of soot, which absorbs sunlight, and some reflecting sulfate. It causes heating of the atmosphere rather than the land surface, weakening the seasonal establishment of a land-ocean temperature gradient which is critical in triggering monsoon onset[19]. Conversely, greenhouse gas forcing is acting to strengthen the monsoon as it warms the northern land masses faster than the ocean to the south. In some future projections, ABC forcing could double the drought frequency within a decade[19] with large impacts, although it should be highly reversible.

Estimation of likelihood under different scenarios

If we pass climate tipping points due to human activities (which in IPCC language are called "large scale discontinuities"[21]), then this would qualify as dangerous anthropogenic interference (DAI) in the climate system. Relating actual regional tipping points to e.g. global mean temperature change is always indirect, often difficult and sometimes not meaningful. Recent efforts suggest that 1 °C global warming (above 1980-1999) could be dangerous as there are "moderately significant"[21] risks of large scale discontinuities, and Arctic sea-ice and possibly the Greenland ice sheet would be threatened[1,22]. 3 °C is clearly dangerous as risks of large scale discontinuities are "substantial or severe"[21], and several tipping elements could be threatened[1]. Under a 2-4 °C committed warming, expert elicitation[3] gives a >16% probability of crossing at least 1 of 5 tipping points, which rises to >56% for a >4 °C committed warming. Considering a longer list of 9 potential tipping elements, Figure 2 summarizes recent information on the likelihood of tipping them under the IPCC range of projected global warming this century.

Figure 2: Burning embers diagram for the likelihood of tipping different elements under different degrees of global warming[23] – updated, based on expert elicitation results[3] and recent literature.



Early warning prospects

An alternative approach to assessing the likelihood of tipping different elements is to try and directly extract some information on their present stability (or otherwise). Recent progress has been made in identifying and testing generic potential early warning indicators of an approaching tipping point[1,24-27]. Slowing down in response to perturbation is a nearly universal property of systems approaching various types of tipping point[25,27]. This has been successfully detected in past climate records approaching different transitions[24,25], and in model experiments[24-26]. Other early warning indicators that have been explored for ecological tipping points[28], include increasing variance[28], skewed responses[28,29] and their spatial equivalents[30]. These are beginning to be applied to anticipating climate tipping points. For climate sub-systems subject to a high degree of short timescale variability ('noise'), flickering between states may occur prior to a more permanent transition[31]. For such cases, we have recently developed a method of deducing the number of states (or 'modes') being sampled by a system, their relative stability (or otherwise), and changes in these properties over time[32].

Applying these methods to observational and reconstructed climate indices leading up to the present, we find that the Atlantic Multi-decadal Oscillation (AMO) index, which is believed to reflect fluctuations in the underlying strength of the thermohaline circulation, is showing signs of slowing down (i.e. decreasing stability) and of the appearance of a second state (or mode of behavior). On interrogating the underlying sea surface temperature data (used to construct the index), we find that recent significant changes are localized in the northernmost North Atlantic, and are investigating the possible relationship with changes in Arctic sea-ice cover. Meanwhile, some other climate indices, e.g. the Pacific Decadal Oscillation (PDO) show signs of increasing stability.

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Catastrophic Climate Change

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Introduction

The question of how to assess prospects of climate change catastrophes has been the focus of a great deal of recent research and debate. An example of the classic conundrum of low probability – high consequences events, a climate change catastrophe is a highly unlikely event, but if it did occur it would severely affect well-being across the world – though it would affect poor countries much more seriously than richer countries.[1] The larger geographical scale of climate change catastrophes distinguishes them from more localized extreme events. The consequences of catastrophes also are in varying degrees very costly, if not possible, to reverse.

Examples of global catastrophes include very large and relatively rapid increases in sea level from faster melting and collapse of ice sheets, slower changes in ocean currents that have insidious effects on weather patterns, and large scale destruction of forests and other ecosystems. fairly rapid loss of global forest cover. Unlike sudden disasters such as earthquakes, the onset of these events is measured in multiple decades or centuries; but once they occur it is impossible to reverse the impacts. Other permanent effects of climate change are anticipated to be increases in the frequency and severities of droughts, floods, and hurricanes, leading to corresponding destruction of crops, water supplies, and coastal infrastructure. While each of these individual events is a more localized disaster, the cumulative effect could be a global catastrophe created by the ―cascading consequences‖ of more localized disasters occurring in relatively quick succession, each amplifying the effects of others.[2]

A key step in evaluating risks of climate change catastrophes is to assess not only the impacts on the physical climate system, but also the consequences in terms of human impacts. The most immediate implication is that while a physical ―tipping point‖ may be reached at some unknown future date T^0, the human impacts will evolve more slowly, reaching an intensity viewed as catastrophic only at some date $T^1 > T^0$. This distinguishes climate change from, for example, the risk of catastrophe posed by a gigantic volcanic eruption, or nuclear war. While a gradual onset of impacts will not prevent a catastrophe if reversal is not possible, it can provide a window of time for major action to avert or adapt to the threat – if signals of the changes are detectable. More fundamentally, the assessment of what constitutes catastrophic human impacts involves not just climate change and earth system science, but

[1] In terms of absolute numbers, losses are likely to be larger in richer nations. As a percentage of GDP, however, less developed countries are likely to face higher damages since most are more dependent on agriculture and less likely to have the resources to adopt measures that could reduce damages.

[2] This possibility appears to have received little systematic attention in reviews of climate change impacts by the IPCC and others, though it figures prominently in discourse about national security consequences of climate change.

also inherent value judgments about what magnitude and speed of consequences are deemed to be catastrophic. For example, the now-often-cited ―scientific near-consensus‖ about the urgent need to hold warming to less than 2°C relative to pre-industrial times reflects more than a natural science evaluation of climate change impacts.

Climate change catastrophes pose a familiar challenge for assessing the impacts of low probability – high impact events: while exact quantification is not possible, the most extreme adverse impacts from climate change—say the worst 1% of scenarios—may account for a large portion of losses in expected value terms. This implies that focusing primarily on a trajectory of more likely anticipated climate change damages may miss an important part of the problem.[3] Yet, these consequences of an unlikely but possible climate change catastrophe need to be weighed against a variety of other risks society faces.

Further complicating the problem is that climate change catastrophes may be better characterized by ignorance than uncertainty. That is, not only do we not know the probability of a particular mega-catastrophe occurring, we do not even know many of the possible outcomes. A catastrophe from climate change could stem from a cause or have impacts that currently receive little attention.[4] Some authors have suggested that this level of ignorance, coupled with the very low probability of an event and the possibility of extremely severe impacts, hamstrings the use of rational-choice based methods for analyzing response options. This in turn requires confronting the possibility that attitudes of the broader public about such events will not align very well with the results of a more systematic evaluation of the pros and cons of different response options, raising questions about what sets of preferences and beliefs should govern policy making.

Climate Change Catastrophes

The most widely discussed large-scale impact of climate change is **global sea level rise**. The collapse of the West Antarctic Ice Sheet (WAIS) or Greenland ice sheets could lead ultimately to a sea level rise of several meters, with consequences great enough to be considered a global catastrophe in the absence of massive and costly relocation because of the number of people living near the coasts. A key uncertainty is how rapidly this change in sea level might occur. Previously it had been thought that such large changes might require much longer than a century, but some recent studies suggest that substantial change could occur in this century. Anthoff et al. (2009) report figures for world losses

[3] For many classes of disasters and catastrophes, the most extreme small percent of the situations represent a significant proportion of the losses. We have witnessed this ―fat tail‖ phenomenon recently with terrorist deaths and losses in a financial crisis. 9/11 and the 2008-09 financial meltdown caused more deaths and dollar losses respectively than all terrorist incidents and financial catastrophes in the post WWII era. With such phenomena, losses are better characterized by a power law than by a normal or even lognormal distribution. The debate about fat tails in relation to climate catastrophes has been a subject of lively recent debate among Weitzman, Pindyck, Nordhaus, and others.

[4] The history of the past 40 years is sobering with respect to the ability to identify catastrophe risks. In 1970, nuclear war would have been the leading contender for any world catastrophe, and looking forward few would have predicted the major looming threats of the current era, which would include not just climate change, but also global pandemics and terrorism.

(based on 1995 baseline conditions) that are relatively small – on the order of 0.5% of world GDP for a 5 m rise. Dasgupta et al. (2007) report figures for developing countries on the order of 6% of GDP, those these estimates do not take account of possibilities for ex ante efforts to mitigate risks. On the other hand, estimates based on historical baselines will tend to under-state the economic impacts of sea level rise by not taking account of likely future growth in the coming years in the share of GDP concentrated in coastal areas.[5]

A second important category of global catastrophe risk involves **disruptions of ocean circulation from climate change,** with potentially disastrous effects on regional weather patterns and long-term climate (Vellinga and Wood 2008). Such impacts are most commonly seen as developing over many hundreds of years. In contrast, **very large-scale ecosystem disruptions** could occur significantly sooner. Changes in ecosystems resulting from changes in temperature and rainfall incidence and increased climate variability have the potential to cause very significant loss of biodiversity—on the order of 20-30% extinction within a few decades. There is also the prospect of major changes in vegetation, in particular, irreversible conversion of forest to grassland, desertification, and acidification of the ocean (Smith, Schneider, Oppenheimer et al. 2009). Another cause for significant concern is the possibility that positive feedback effects in the climate change process itself could occur (e.g., liberation of trapped methane from ice, rapid increases in CO_2 from vegetation dieback, or increased heat absorption as glaciers retreat), causing the abovementioned changes to occur more rapidly.

There also has been significant scientific research on how climate change can effect more localized disasters, such as heat waves, flooding, droughts, and changes in hurricane frequency or intensity. Less understood is how **a number of smaller disasters** all occurring over a relatively short time period could mutually reinforce each other in such as way that the **resulting "cascade of consequences" becomes a global catastrophe**. Extreme events can have secondary consequences that generate substantial amounts of additional damages; secondary consequences in turn can trigger tertiary consequences that further amplify the adverse consequences; and so on. One example would be if increased drought from climate change in different regions successively caused a series of local food shortages to occur in close proximity, leading to political instability, a breakdown of civil order, large-scale migration for survival, and regional conflicts. Another example could be a series of local fires occurring in climate-stressed forests and grasslands overly widely dispersed areas, adding up to a large-scale destruction of resources, ecosystem services, and livelihoods over a large area.

The compounding or amplifying effects of individual adverse impacts would be the result of exceeding the resilience of a number of local socioeconomic systems in rapid succession. More frail components of socioeconomic systems, such as marginal subsistence agriculture, represent potential places of vulnerability. Cascading-event catastrophes could occur much more rapidly than the slower-onset global impacts discussed above, especially as climate change accelerates and greater negative impacts occur at local scales. It is possible that more comprehensive local monitoring of disaster risks may facilitate the

[5] Using 1995 data, it has been estimated that around 400 million people would be impacted by a 5 m rise in sea level and that a WAIS collapse in 100 years could cause, at the peak, 350,000 forced migrations a year for a decade (Nicholls, Tol and Vafeidis 2008).

development of early warning indicators for cascading catastrophes. For example, if several years of historically unusual drought weakened agricultural systems in many vulnerable parts of the world, there would be a stronger basis for concern about cascading consequences than if agricultural failures were not occurring in such rapid succession. However, the time interval for action to avert the potential catastrophe could be short.

Traditional responses to the risk of extreme events are of limited value in mitigating risks of a mega-catastrophe. The underlying changes in the climatic system could not be reversed over any time scale relevant for decision-makers. Traditional insurance mechanisms will not function effectively for this type of event, because the risks are ―systemic‖ and cannot effectively be reallocated to diversify. Moreover, significant international transfers from richer to more vulnerable poorer countries are unlikely when a catastrophe affects broad swaths of the world.

Evaluating Climate Change Catastrophe Risks

The traditional economic model for decision making under uncertainty is expected utility theory, in which decision makers maximize the utility they receive from potential outcomes weighted by the probability the outcomes will occur. In the climate change economics literature, GHG abatement policies with the expected net benefits over time are identified using dynamic Integrated Assessment Models (IAMs) that compare the anticipated costs of abatement with avoided damages from climate change over time. By and large these models are deterministic and are used for scenario-based comparisons of policies under different assumptions about climate change damages and abatement costs. However, a literature has developed in which catastrophes are treated as (usually known) large-scale rapid-onset economic damages with an uncertain date of occurrence, the probability of which increases as atmospheric GHG concentrations rise.[6]

A common finding in these studies is that while the risk of such catastrophes increases the expected economic benefits of more rapid GHG mitigation, the effect is not that significant qualitatively unless the probability of nearer-term catastrophe is quite high, the size of the catastrophe is truly astronomical, or the discount rate used to value future catastrophic impacts is quite low. The scientific information on catastrophes summarized above indicates that catastrophes are extremely unlikely in any time frame short of several decades at the very least, and that while the ultimate effects may indeed be huge, the most severe impacts will develop only gradually. Until scientific understanding of climate change catastrophes leads to stronger findings on their proximity and severity, the choice of discount rate will be the most important determinant of the cost of future catastrophes in the expected-utility framework.

The discount rate issue in turn continues to be very hotly debated, and only a very brief summary of key points is offered here. Two strands of positive analysis has argued for applying a lower discount rate to longer-term climate change costs, including catastrophes, than might be inferred from research on consumer time preference or rates of return on investment. One is that individuals may discount the future hyperbolically, so rates of discount decline and ultimately plateau at a fairly low number as one

[6] References – Kverndokk et al, Pizer, Nordhaus. Earlier foreshadowing by Manne.

goes out into the future. The other is that when one accounts for the higher marginal utility of income for the poor facing more adverse impacts from climate change, then under reasonable assumptions the effective time discount rate after adjusting for distributional differences is reduced. In addition, if climate change has the most severe effects on longer-term economic growth when growth itself is more likely to be weak, then policies to reduce the threat of catastrophe will have a lower effective discount rate because of their contribution to reducing intertemporal economic risk.[7]

Even with these considerations, however, the resulting implied discounting of future over current returns may not be small enough for catastrophes to carry major weight in evaluating the potential impacts of climate change. Unless the discount rate is under 1%, and perhaps even close to zero, severe future consequences that will not arrive for some time and are not world-threatening may still be too ―telescoped.‖ Stern and others have addressed the issue of discounting by using normative arguments to suggest a discount rate at or near zero is in fact appropriate. Two other arguments, not so dependent on normative precepts, may also add weight to the importance of catastrophe risks in evaluating climate change impacts.

Hypothesis 1: People are Not Expected Utility – Maximizers

There is a growing literature from behavioral economics and psychology which demonstrates that individuals do not consistently make decisions according to the expected utility paradigm.[8] If individuals are only boundedly rational, they have neither the time nor the capacity to fully assess the consequences of decisions. In that case, individuals adopt certain rules of thumb and mental shortcuts to make decisions. These so-called heuristics can lead to choices that depart from predictions of expected utility theory.

When thinking about possible disasters, it has been found that people tend to be over-optimistic, thinking negative outcomes are less likely to happen to them. When a risk is highly emotional, however, people can disregard probabilities altogether, treating all outcomes as equal (―probability neglect‖). Individuals also seem to place an added value on certainty, preferring to reduce a small risk to zero by more than they value reducing a larger risk by a greater amount. Errors of commission are viewed as worse than errors of omission. This can lead to a tilt to the side of inaction.

Experimental also has found that context matters, often significantly, a when making decisions. For instance, when probabilities are unknown and must be estimated, individuals have been found to assess an event as more likely when examples come to mind more easily (the ―availability heuristic‖). People can disproportionately prefer to maintain the status quo in their choices, even if conditions or options change. Individuals sometimes ―anchor‖ their preferences on an available piece of information, and fail to update their assessments adequately in the face of new information. Individual choices are also

[7] [add references] Strictly speaking, the second and third arguments are not about the actual rate of time preference, but rather about how factors related to distributional impacts and risk that enter the maximand of the intertemporal utility calculation affect the implied discounting of future over current returns.

[8] This discussion is taken from Kousky et al (2009), which contains references to the relevant behavioral economics literature.

strongly affected by the way that information is presented. Thus, individuals may make different choices for the same decision if it is merely phrased differently (—framing effects‖). Choices depend upon the extent to which a risk evokes feelings of dread. Personal utility also is sensitive to individuals' perceptions of equity and fairness.

These various behavioral attributes can imply higher or lower values attached to catastrophe risks than would be implied by expected utility theory. The former would follow from dread or the evaluation of all catastrophes as roughly equal in likelihood. The latter would follow from optimism bias, or a preference for reducing small and familiar risks to zero over reducing more substantially an unfamiliar risk – of which climate change catastrophe certainly is an example. While the direction of bias has to be assessed empirically, the existence of these various —non-rational‖ attitudes raises an important but not new question for evaluating climate change catastrophe risks in setting public policy: if decision makers believe they have better information than the general public and that they are less subject to emotional biases, to what extent should their valuation of alternatives supersede those of members of the general public?

Hypothesis 2: People are Non-Egoistic Expected Utility – Maximizers

A second approach that has been taken in the literature for addressing long-term threats posed by climate change is to see individuals today, imperfect information and all, as interested in more than maximizing the discounted present value of their lifetime expected utility streams. One can broadly define this as altruistic preferences, but this label can cover several different forms of preferences.

A traditional approach to altruistic preferences is to include some measure of next-generation or other future utility in the preferences of members of the current generation. In this setting, individuals will weigh the potential costs of a climate change catastrophe in terms of its anticipated impacts on future welfare, as well as the possibly slight impact on current individuals' egoistic well-being. Consequently, individuals will derive utility in part from the —bequest they leave to the future in terms of a lowered (endogenous) risk of a climate change catastrophe. However, there are both theoretical and empirical reasons to expect individuals to discount the welfare of future generations relative to their own egoistic welfare. This takes us back to the question previously mentioned in the context of time preference, as to how powerful an influence this form of altruism might be in the current generation's assessment of risks of climate change catastrophes.[9]

A second approach is to depart from a purely utilitarian framework by supposing that individuals see themselves (or should do) as having a moral obligation to future generations. This mixing of obligations and conventional utilitarian motivations implies some degree of lexicography in individuals' preferences – or, critics of utilitarianism might say, an innate failure of the standard economic model to describe what really motivates people. In this view, if a potential future catastrophe threatens to impose a

[9] Current individuals also could believe, as Schelling for example has suggested, that other kinds of bequests to the future would have higher value; or they could further discount bequests of a less risky climate out of concern that unless the —chain of obligation‖ is maintained, something impossible to assure, the sacrifice made today would be wasted in the future.

morally inacceptable burden on the future, people will be (or at least can be) motivated to endure potentially extra-ordinary sacrifices to reduce the threat. The expression of that moral sentiment by individuals as citizens and stewards, versus utilitarian consumers, would be found through public choice exercises like voting for tough restrictions on future GHG emissions.

This conception is both stimulating and frustrating, since it does not offer any straightforward way of assessing how economically significant is the threat of a future climate change catastrophe. Aside from uncertainty about what the triggering level of threat to the future might be, does one regard current almost universal reticence to support tough GHG restrictions as due to (correctable) moral failing? Lack of information? Lack of leadership? The result of rational leadership, because the threat of climate change is seen as less significant than other threats or because international collective action problems have not been solved?

A third possible approach that has received less attention is that individuals have preferences that include some notion of —planetary health‖ as a global public good. Rather than seek to describe concern about risks of catastrophe from climate change as deriving only from more fundamental concerns for intergenerational altruism or fairness, one could posit that individuals derive some direct benefit from having greater confidence in the ability of planetary systems to remain undisrupted, without the need to unpack the rationales in terms of future human well-being, satisfaction of moral sentiment, or a pure existence benefit. This approach allows one to sidestep some of the difficulties encountered in either the altruistic utilitarian or moral-obligations conceptions. In particular, the normative approach to setting discount rates can be embedded in a framework of preferences without having to be an ad hoc add-on.[10] However, this does not get around the huge empirical problems in assessing the value that members of the current generation might place on reducing risks of future climate change catastrophes.[11]

Catastrophe Risks and Rational Choice Approaches to Policy

While it is certainly possible to debate the capacity of expected –utility types of analyses to adequately capture the social opportunity cost of climate change catastrophe threats, it is in cases like this that a disciplined application of rational-choice based analysis more broadly defined can prove most useful. A thoughtful, systematic, and transparent weighing of benefits and costs, broadly defined, is at the heart of such an approach. The presence of —deep‖ uncertainty or ignorance about the types and likelihoods of potential catastrophes means that we must include, in addition to sensitivity analysis on these

[10] A fundamental criticism of conventional expected-utility analysis for assessing future climate change risks is that it combines conventional time-preference considerations in assessing the opportunity cost of reducing threats with the explicitly ethical question of how much the current generation will feel willing or bound to do in protecting the future.

[11] Ideas like this arise often in literature on environmental stewardship, but I am not aware of many treatments of the idea in economic terms. One example is the paper by Kopp and Portney [ref to add], who describe a thought experiment in which individuals value —well being of the future,‖ and the willingness-to-pay for that value can be discerned through a stated preference valuation effort. While one can debate the merits of the valuation approach even in a thought experiment, the concept is very similar to what I am trying to describe here. Unfortunately, the question of how one would ascertain such valuation remains a barrier to empirical implementation of the concept.

characteristics, focused analysis of the robustness and flexibility of options in addition to the benefits and costs. With respect to what seem to be behavioral biases in the assessment of catastrophe risks by individuals, decision makers must make (and then defend) informed judgments on behalf of those they serve as to when the seeming biases reflect a high degree of economic risk aversion, or dread, and when the biases reflect other factors (framing effects, optimism bias, and the like) that can be viewed as inaccurate comprehension of the tradeoffs involved.

Posner (2005) argues that uncertainty over benefits and costs should not prevent using the basic structure of cost-benefit analysis for evaluating and comparing options, but that this should be framed in a —tolerable-windows‖ approach. This involves using a range of plausible risk estimates to help identify levels of spending on reducing risk for which benefits clearly exceed the costs, for which costs clearly exceed benefits. Policies then can be designed with the goal to remain in this window.[12] This approach does not provide or depend on —a number‖ for how to evaluate the impacts of potential future climate change catastrophes. In particular, it does not treat them as largely irrelevant economically given their low probabilities and long time frames to be realized. Instead it provides flexibility as to how different considerations about climate change catastrophes are brought into the assessment, including risk aversion and concerns about future sustainability as well as costs of risk mitigation, while insisting on transparency and a persuasive argument for how these considerations are to be addressed.

[12] This idea is akin to value-of-information approaches. If one has some confidence in the evaluation of costs of different policies but great uncertainty about the potential benefits, one could investigate how large the potential benefits might have to be to make a case for the selection of one set of options over another in a portfolio. Similarly, if the benefits are reasonably well understood conditional on a catastrophe occurring, but there is uncertainty about the probability of a catastrophe, then one can ask how large the probability would have to be to justify a particular portfolio of actions.

Natural Capital and Intra- Generational Equity in Climate Change

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Introduction

There are two dimensions of equity that are relevant in an evaluation of the impact of climate change – inter- and intra-generational. It is the former that has been most discussed in the literature to date – all of the extensive debate about the choice of a discount rate in climate models is in effect a debate about intergenerational equity and how to model our concerns about this. And clearly this is very relevant in a climate context – emissions made today will affect generations not yet born, so that issues of intergenerational fairness are central to any discussion of climate policy. But intragenerational issues loom large too: climate change is an external cost imposed largely by rich countries on poor ones, and in addition there is evidence that in any given country it affects poor people more than rich. This dimension of climate change has not been extensively discussed.

Climate change affects our stock of natural capital – for example, the IPCC has estimated that by 2100 in the range of 30-40% of currently extant species may be driven extinct by climate-induced changes in their ecosystems. This would represent a massive transformation of the biospehere, one unprecedented in human history. Glaciers and snowfields are also likely to diminish greatly in extent, affecting water supplies to many regions. Changes like this in our natural capital could have far-reaching consequences, and these are likely to be felt more by poor than by rich countries, and more by poor than rich groups in any country (World Bank 2006). So intra-generational equity and natural capital impacts are related: the latter is likely to reinforce concerns about the former. An important question here is whether some other form of capital – human, intellectual or physical, can replace natural capital. To the extent that this is possible, it may be possible to ameliorate some of the intra-generational equity impacts of climate change. In the notes that follow, I begin to develop some of these points, making suggestions about how they might be modeled.

Equity and Discounting

As anyone who has spent even a short time on the economics of climate change must be aware, a central issue is the choice of the pure rate of time preference (PRTP), to be distinguished clearly from the consumption discount rate (CDR). The PRTP is the δ in the expression $\int_0^\infty u(c_t)e^{-\delta t}dt$ where c_t is aggregate consumption at time *t*, *u* is a utility function showing strictly diminishing returns to consumption and we are summing discounted utility over all remaining time.

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The other discount rate concept, the CDR, is the rate of change of the present value of the marginal utility of consumption, that is, the rate of change of $\frac{e^{-\delta t} du(c_t)}{dc_t}$. For the case of a single consumption good - and we will turn to the case of multiple goods later - it follows from well-known arguments going back to Ramsey [1928] (see Heal [2005] for a review) that this is equal to the PRTP plus the rate of change of consumption times the elasticity of the marginal utility of consumption:

$$\rho_t = \delta + \eta(c_t) R(c_t) \qquad (1)$$

where ρ_t is the consumption discount rate applied to consumption at time t, $\eta(c_t) = -\frac{cu''}{u'} > 0$ is the elasticity of the marginal utility of consumption and $R(c_t)$ is the rate of change of consumption at time t. (Here $u' = \frac{du(c)}{dc}$ and $u'' = \frac{d}{dc}u'$.)

What do these two discount rates mean? The PRTP δ is the rate at which we discount the welfare of future people *just because they are in the future*: it is, if you like, the rate of intergenerational discrimination. Note that there are at least two reasons why we may wish to value increments of consumption going to different people differently: one is that they live at different times, which is captured by δ, and the other is that they have different income levels, which we discuss shortly.[2] A PRTP greater than zero lets us value the utility of future people less than that of present people, *just because they live in the future rather than the present*. They are valued differently even if they have the same incomes. Doing this is making the same kind of judgment as one would make if one valued the utility of people in Asia differently from that of people in Africa, except that we are using different dimensions of the space-time continuum as the basis for differentiation.

That an increment of consumption is less important to a rich person than to a poor person has long been a staple of utilitarian arguments for income redistribution and progressive taxation (see Sen [1973]), and is almost universally accepted. This is reflected in the diminishing marginal utility of consumption, and the rate at which marginal utility falls as consumption rises is captured by $\eta(c_t)$. Equation 1 pulls together time preference and distributional judgments, or considerations based on inter- and intra-generational judgments: the rate at which the value of an increment of consumption changes over time, the CDR ρ_t, equals the PRTP δ plus the rate at which the marginal utility of consumption is falling. This latter is the rate at which consumption is increasing over time $R(c_t)$ times the elasticity of the marginal utility of consumption $\eta(c_t)$.

[2] We could also value them differently for all manner of other reasons - differences in nationality, ethnicity, and proximity either physically or genetically. In general we don't do these things, at least explicitly, which to me makes it strange that we do explicitly discriminate by proximity in time.

Equity and Climate Change

As we have just seen, there are two dimensions of equity that are important in the context of climate change: equity between present and future generations, the aspect that has been most extensively discussed, and equity between rich and poor countries or groups, both now and in the future – inter- and intra-generational issues. This second dimension is invisible in aggregative one-good models, which is one reason why we need a many-good model to talk seriously about climate change. The discussions below will reinforce the need for some measure of disaggregation in the analysis of the economics of climate change if we are to grapple with equity issues.

The parameter η the elasticity of the marginal utility of consumption, summarizes our preference for equality: it determines how fast marginal utility falls as income rises. There are two ways in which this affects the case for action on climate change.

As η rises, the marginal utility of consumption falls more rapidly. If consumption is growing over time, then this means that the marginal utility of future generations falls more rapidly with larger values of η and therefore we are less concerned about benefits or costs to future generations. We are less future-oriented - the consumption discount rate ρ is higher - and so place less value on stopping climate change. So via this mechanism, *a stronger preference for equality leads to a less aggressive position on the need for action on climate change*. Preferences for equality and action on climate change are negatively linked here.

There is another offsetting effect, not visible in an aggregative model. Climate change is an external effect imposed to a significant degree by rich countries on poor countries. The great majority of the greenhouse gases currently in the atmosphere were put there by the rich countries, and the biggest losers will be the poor countries - though the rich will certainly lose as well. Because of this, *a stronger preference for equality will make us more concerned to take action to reduce climate change*.

So we have an ambiguous impact of a stronger preference for equity on our attitude towards climate change. Via the mechanism captured in the formula for the consumption discount rate, equation 1, it makes us less future oriented - provided consumption is growing. (If consumption were to fall, it would make us more future oriented, and if consumption of some goods were to rise and that of others to fall, the effect would be a priori unclear.) And via our concern for the poor countries in the world today it makes us more future-oriented. Unfortunately, without exception analytical models capture only the first of these effects. They are aggregative one-sector models or models with no distributive weights and so their operation does not reflect the second mechanism mentioned above. This explains the really puzzling and counter-intuitive result that a greater preference for equality in Nordhaus's DICE model leads to less concern about climate change.

To capture fully the contradictory impacts of preferences for equality on climate change policy, we need a model that is disaggregated both by consumption goods and by consumers, allowing us to study the consumption of environmental as well as non-environmental goods and also the differential impacts of climate change on rich and poor nations.

Natural Capital and Climate Change

Return to equation (1) for the consumption discount rate. Note that if consumption were *falling* rather than *rising* over time (the latter being the universal assumption in IAMs), then the second term in the expression for ρ_t would be negative and the CDR could in principle be negative, that is the value of an increment of consumption could be rising over time rather than falling. We would not be discounting but doing the opposite, whatever that is. It is not impossible that in a world of dramatic climate change and environmental degradation, consumption might fall at some point. It is even more likely that *some aspects of consumption, or the consumption of some social groups,* would fall while other continue to rise - recognizing this requires that we treat consumption as a vector of different goods that can be affected differently by climate change. For an early recognition of this point see Fisher and Krutilla [1975], who comment that increasing scarcity of wilderness areas may drive up our valuation of them. A more detailed analysis in the context of a growth model is in Gerlagh and van der Zwaan [2002], who make the interesting point that with limited substitutability between environmental and manufactured goods and the growing scarcity of environmental goods, there is likely to be a version of Baumol's disease - an ever larger portion of income being spent on non-manufactured goods.

Let's follow this line of thought and disaggregate consumption at date t into a vector $c_t = (c_{1,t}, c_{2,t}, \ldots, c_{n,t})$ of n different goods. (We will mention briefly later the case in which these are the consumption levels of different countries or social groups.) Utility is increasing at a diminishing rate in all of these goods and is a concave function overall. In this case we have to change equation 1 for the consumption discount rate. Now there is a CDR for each type of consumption and we have n equations like equation 1, with a CDR for each good i equal to the PRTP plus the sum over all goods j of the elasticity of the marginal utility of consumption of good i with respect to good j times the growth rate of consumption of good j:

$$\rho_{i,t} = \delta + \eta_{ii}(c_t)R(c_{i,t}) + \sum_{j\neq i}\eta_{ij}(c_t)R(c_{j,t}) \qquad (2)$$

where $\rho_{i,t}$ is the CDR on good i at date t, $R(c_{i,t})$ is the rate of change of consumption of good i at date t, and $\eta_{ij}(c_t)$ is the elasticity of the marginal utility of good i with respect to the consumption of good j (see Heal [2005] for details: the most general framework of this type can be found in Malinvaud's classic paper [1953]). The own [illegible] t the cross elasticities $\eta_{ij}(c_t)$, $j\neq i$, are zero if the utility function is additively separable and can otherwise have either sign.

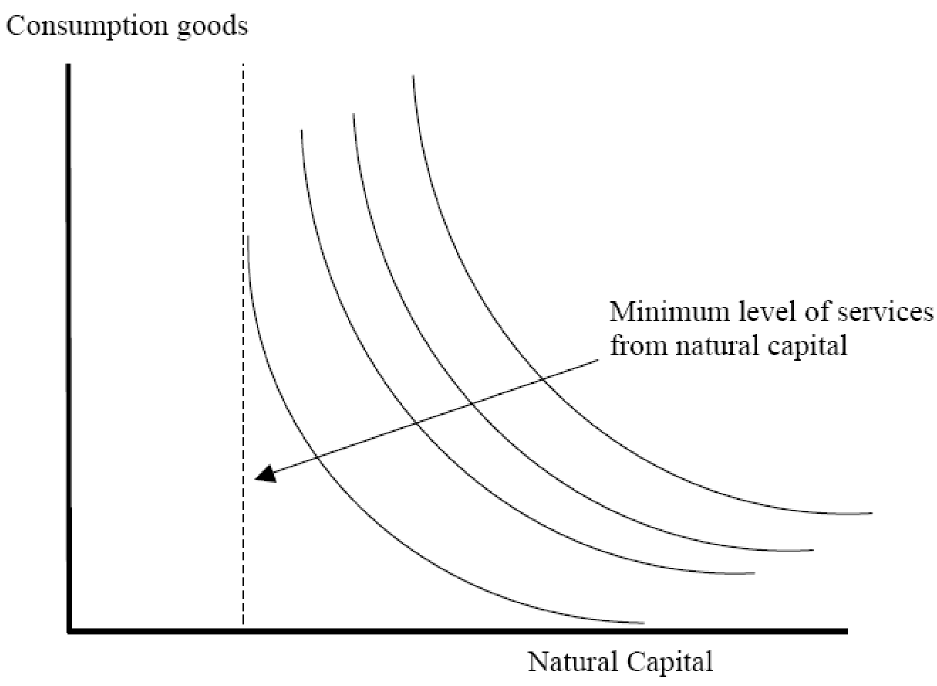
As an illustration consider the constant elasticity of substitution utility function

$$\left[\alpha c^{\sigma} + (1-\alpha)s^{\sigma}\right]^{\frac{1}{\sigma}} \qquad (3)$$

Here we can think of c as produced consumption and s as natural capital, an environmental stock that produces a flow of ecosystem services. (See Barbier and Heal for a discussion of this concept [2006] and the World Bank for a detailed review of the role of natural capital in the growth process [2006].) In this case the cross elasticity of the margi[illegible]on depends on whether c and s are substitutes or complements. For an elasticity $\sigma > 1$ they are substitutes and the cross elasticity is positive, and vice versa.

Let's test our intuitions on this. Take the case where natural capital and produced consumption are highly complementary, so that indifference curves are near to right angled and the elasticity σ is close to zero. Then the cross elasticity is negative. This means that if the stock of natural capital is rising then this reduces the consumption discount rate on the regular good. Conversely if the availability of natural capital is falling then this raises the consumption discount rate on the consumption good. These results make sense: because of the assumed complementarity, an increase in the amount of the environmental good will raise the marginal utility of the consumption good and so tend to lower the consumption discount rate, and vice versa. Of course, the own elasticity on natural capital is positive so that if the availability of this good is falling then this will tend to make its own consumption discount rate negative.

Whether produced goods and environmental services are substitutes or complements in consumption is not an issue that has been discussed in the literature, as with the few exceptions mentioned above people have worked with one-good models. There do however seem to be reasons to suppose that complementarity is the better assumption, with $\sigma < 1$. Dasgupta and Heal [1979], following Berry Heal and Salamon [1978], suggest that in production there are technological limits to the possibility of substituting produced goods for natural resources. In particular we invoke the second law of thermodynamics (Berry and Salamon are thermodynamicists) to suggest that if energy is one of the



inputs to a production process, then there is a lower bound to the isoquants on the energy axis. Similarly one can argue that certain ecosystem services or products, such as water and food, are essential to survival and cannot be replaced by produced goods. There are therefore lower bounds to indifference curves along these axes, implying if the utility function is CES that $\sigma < 1$.

The figure illustrates this idea: it shows indifference curves for a two-argument utility function, consumption of produced goods and of ecosystem services, as in equation 3 above. There is a minimum level of ecosystem services needed for survival - think of this as water, air, and basic foodstuffs, all of which are ultimately produced from natural capital. For low welfare levels there is no substitutability between these and produced goods, so that indifference curves are close to right angled. At higher welfare levels where there are abundant amounts of both goods there is more scope for substitution. Taken literally, this implies that the elasticity of substitution is not constant but depends on and increases with welfare levels. This of course is not reflected in the CES function such as 3. A function with these properties is

$$\left[\alpha c^{\sigma} + (1-\alpha)(s-\varepsilon)^{\sigma}\right]^{\frac{1}{\sigma}} \qquad (4)$$

which is simply the CES function we noted before, with the zero of the ecosystem service axis transformed by $\varepsilon > 0$. Utility is not defined for $s > \varepsilon$. Relative to the transformed origin $(\varepsilon,0)$ there is still a constant elasticity of substitution σ but relative to (0,0) the elasticity is not constant. For $\sigma > 1$, every indifference curve, every welfare level, can be attained with only ε of ecosystem services, whereas with $\sigma < 1$ greater welfare levels require greater levels of ecosystem services (and of consumption goods).

These ideas can be applied to modeling equity: it is generally recognized that poor countries, or poor groups within countries, are more dependent on natural capital and its services than are richer groups (World Bank [2006]). They have less capacity to substitute alternative goods for the services of natural capital and so show more complementarity between natural capital and other goods. In terms of the figure, their indifference curves are lower and closer to being right angled. This means that they have different consumption discount rates from other groups: if the stock of natural capital is falling then they will have higher consumption discount rates on the common consumption good. In this sense they will appear to be more impatient. Of course as noted above their discount rate on natural capital will be negative, so we will have the paradox of an apparently impatient group – with respect to the consumption good – being willing to invest for low returns in natural capital.

A Sterner Perspective

It's worth looking in more detail at the Sterner and Persson development of this point [2007]. They talk about the effect of changes in relative prices rather than consumption of produced and environmental goods, but the point is the same. If we consume both produced goods and the services of the environment, as in the utility function 3, then we can expect that with climate change environmental services will become scarce relative to produced goods and therefore their price will rise relative to that of produced goods (the "environmental Baumol disease" that Gerlagh and van der Zwaan refer to [2002]). Consequently the present value of an increment of environmental services may be rising over time, and the consumption discount rate on environmental services may thus be negative, precisely the point that we were making in equation 2 above. This could be the case even with a high PRTP, which is the main point of the Sterner and Persson paper. They also present an interesting modification of Nordhaus's DICE model to incorporate this point. They replace the standard utility function, which is an isoelastic function of aggregate consumption, by a CES function along the lines of equation 3 above, but modified to reflect a constant relative risk aversion:

$$\left[(1-\gamma)c^{1-1/\sigma}+\gamma s^{1-1/\sigma}\right]^{(1-\alpha)\sigma/(1-\sigma)}/(1-\alpha)$$

They assume that the supply of environmental services is negatively affected by temperature according to the square of temperature, and that the share of environmental goods in consumption is about 20%, use these assumptions to calibrate the modified DICE model and and then run the model with the PRTP used by Nordhaus. Their runs show that even with such a high PRTP the presence of an environmental stock that is damaged by higher temperatures radically transforms the optimal emissions path of CO and leads to a vastly more conservative policy towards climate change, with emissions both staying lower and falling faster. In fact it leads to a more aggressive reduction in greenhouse gases than recommended by the Stern Review.

Natural Capital and Production

I have emphasized so far that natural capital can affect human welfare directly, and needs to be thought of as an argument of the welfare function. Natural capital also affects a nation's production possibilities: I mentioned above changes in hydrology such as melting of glaciers and reduction in winter snowfields, both of which are already in evidence and are affecting agriculture in some regions. They will affect it further over the coming decades. This is quite separate from any impact that changes in temperature and precipitation may have on agriculture. Other changes in natural capital will probably affect agriculture – changes in species abundance and distribution, for example, can affect whether birds and insects pollinate crops.

Modeling Different Groups

I commented above that equation 2 can be given a different interpretation: instead of

$$\rho_{i,t}=\delta+\eta_{ii}\left(c_t\right)R\left(c_{i,t}\right)+\sum_{j\neq i}\eta_{ij}\left(c_t\right)R\left(c_{j,t}\right) \quad (2)$$

the subscripts i and j referring to different goods, they can be taken as referring to the amounts of a single good consumed by different groups – these could be social groups within a country or they could be different countries. I this case we have different consumption discount rates for each group's consumption, and the elasticities now indicate how the marginal valuation of consumption by one group depends on the consumption levels of others. Do we value on increment of consumption to the poor more if everyone else is very rich than if most others are also poor? Presumably the answer to this is yes, but these are issues that have not featured at all in the discussions to date.

Choosing η

The elasticity of the marginal utility of consumption plays a central role in much of our discussion. Unfortunately this variable plays two roles in our models: it expresses our distributional preferences, which is the way we have been using it here, and it also expresses our aversion to risk. Most empirical estimates of the value of η come from studies of behavior in the face of risk, but it seems clear that these two interpretations of η are really quite different, and that our aversion to risk tells us little if anything about our preferences for income equality. Given this, we need to find a way of expressing preferences that does not conflate distributional and risk preferences. Recursive formulations such as that of Kreps and Porteus are relevant here.

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Managing Climate Risks

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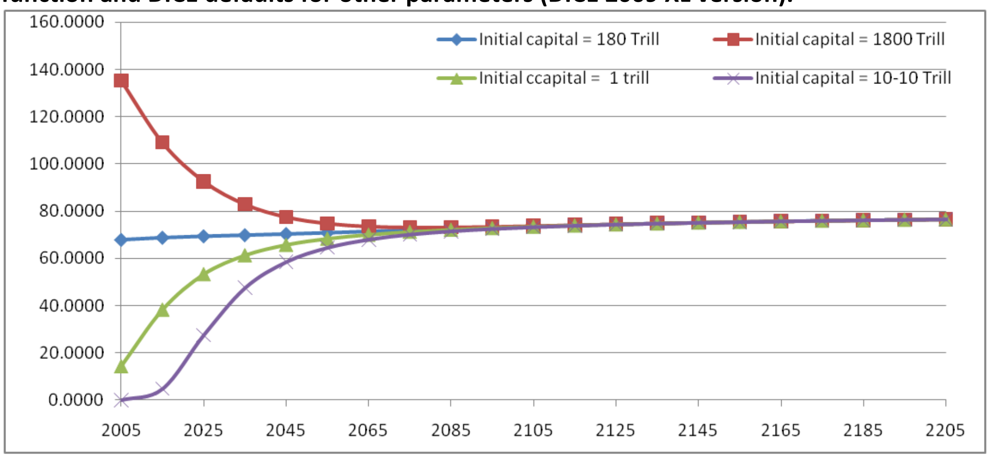
Many Integrated Assessment Models (IAMs) maximize the present value of consumption, equating the marginal benefits of abatement in terms of reduced climate damages with the marginal costs of reducing emissions. Every trader, banker, and investor knows that maximizing expected gain entails a trade-off with risk. According to the theory of rational decision, preferences can always be represented as expected utility, hence from this viewpoint, any aversion to risk could be folded into the rational agent's utility function. This theory, recall, applies to rational *individuals*; groups of rational individuals do not comply the axioms of rational decision theory. The fact is that 'professional risk taking organizations' do manage risk, and not by bending the utility function of a representative consumer. Rather, they employ techniques like value at risk, and optimize expected gain under a risk constraint. Managing risk is a problem of group decision.

Weitzman (2009) has recently called attention to the risks of climate change, arguing that current approaches court probabilities on the order of 0.05~0.01 of consequences that would render life as we know it on the planet impossible. What is the plan to manage this "tail risk"? Risk management shifts the research question from 'how does the optimal abatement level change for different parameter values?' to 'how does our policy choice fare under the range of potential future conditions and how can we buy down the risk of catastrophic outcomes?' As such, it places the quantification of uncertainty in the foreground. Uncertainty quantification is more than a modeler putting distributions on his/her model's parameters. The antecedent question reads: 'is it the right model? What is the model uncertainty?' Failing a definitive answer to that question, *stress testing* our current models for their ability to handle tail risks, and exploring *canonical model variations* are essential steps prior to quantifying uncertainty on parameters. Gone are the days when quantification of the uncertainties was left to the modelers themselves; at the state of the art, quantification is done by *structured expert judgment* in a rigorous and transparent manner.

Stress Testing

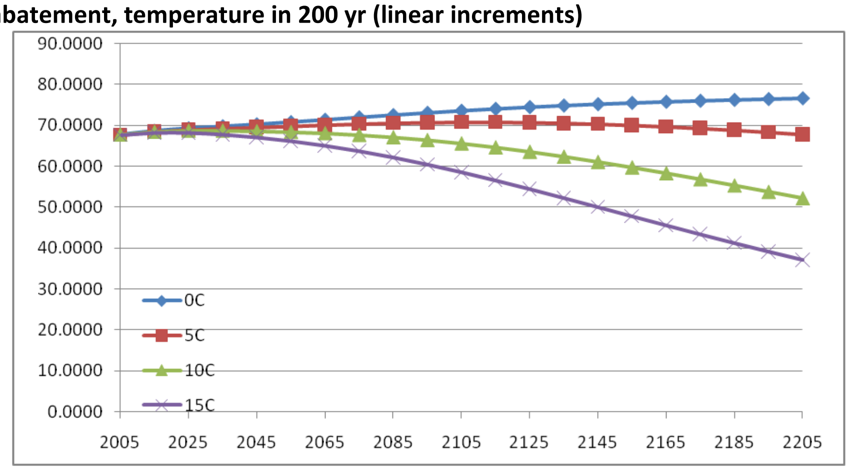
Stress testing is preformed to check that models remain realistic and capture the relevant possibilities when their parameters are given extreme values. Many IAMs specify economic damages as a function of temperature change, and model their impact on output and utility. For example, damages at time t induced by temperature change T(t) from pre-industrial mean temperature are represented in DICE as factor that reduces economic output: $1/[1 + 0.0028388T(t)^2]$. The standard Cobb Douglas production function expresses output as a function of total factor productivity, capital stock and labor. Capital depreciates at rate 10%, and is augmented by savings (in the DICE "Base" case the savings rate is optimized with damages set equal to zero, then damages are reinstated). Temperature induced damages and abatement efforts reduce output. Setting damage and abatement equal to zero, an illustrative stress test of the Cobb Douglass model with constant population, constant total factor productivity and DICE values for other parameters is shown in Figure 1. Four output trajectories with initial capital ranging from 10 times the DICE value ($1800 Trill) to $100 ($$1.6\times10^{-8}$ for each inhabitant). The limiting capital value is independent of the starting values – with a vengeance: the four trajectories are effectively identical after 60 years. Such obviously unrealistic consequences underscore the need for circumscribing the empirical domain of application of these simple models. Put the factories and laborers on the Moon and they will produce nothing; other things are involved. Regardless whether the model adequately describes small departures from an equilibrium state, its use for long term projections inevitably entails this sort of behavior and putting uncertainty distributions on the model's parameters will not change that.

Figure 1. Output gross of abatement cost and climate damage ($trill 2000 USD) Base case, no temperature damage, no abatement, constant population, constant total factor productivity (0.0307951), initial output from production function and DICE defaults for other parameters (DICE 2009 XL version).



A second stress test examines the effect of adding temperature induced economic damages, again without abatement. With $180 Trill initial capital, we assume that temperature increases linearly, leaving other parameters as in the previous case. Figure 2 shows four economic output trajectories, corresponding to temperature increases of 0, 5, 10, and 15 degrees Celsius in 200 years.

Figure 2. Output after damages before abatement, initial capital = 180 $trill, constant population, constant productivity, no abatement, temperature in 200 yr (linear increments)



No scientist claims that life as we know it could exist with 10°C global warming. With a steady temperature rise leading to 10°C above pre-industrial levels in 200 years, this model predicts that output would be reduced to 68.% of its value without temperature rise. Such projections seem a bit sanguine. The essential feature is that climate induced damages hit only economic output; as a result capital can never decrease faster than its natural depreciation rate, and this rate of decrement is reached only for infinite temperature. Again, putting uncertainty on other model parameters may cloud this picture, but will not change this feature.

Canonical Model Variation

It is often noted that simple models like the above cannot explain large differences across time and geography between different economies, pointing to the fact that economic output depends on many factors not present in such simple models. To "save the phenomena" researchers have proposed enhancing the basic model with inter alia social infrastructure, government spending, human capital, knowledge accretion, predation and protection, extortion and expropriation (see Romer (2006), chapter 3). Before proliferating this model, however, it is well to reflect on its fundamental assumptions about damage, capital and output. Could different model types with comparable prime facie plausibility result in macroscopically different behavior?

We illustrate with one variation based on the following simple idea: Gross World Production (GWP[trillion USD 2005]) produces pollution in the form of greenhouse gases; pollution, if unchecked, will ultimately destroy necessary conditions for production. This simple observation suggests that Lotka Volterra type models might provide a perspective which an uncertainty analysis ought not rule out. The quantity of anthropogenic greenhouse gases in the atmosphere at year t, GHG(t) [ppm CO_2], is the amount in the previous year, less what has decayed at a rate, say, 0.0083, plus any new emissions in time period t. Assume that new emissions are a fixed fraction, say, 0.024 of GWP (Kelly and Kohlstadt 2001). Different values can be found in the literature, but these are representative. Real GWP has grown at an annual rate of 3% over the last 48 years (this includes population growth); assume that this growth is decreased by a damage function D of temperature T, and ultimately of GHG, this gives the following system:

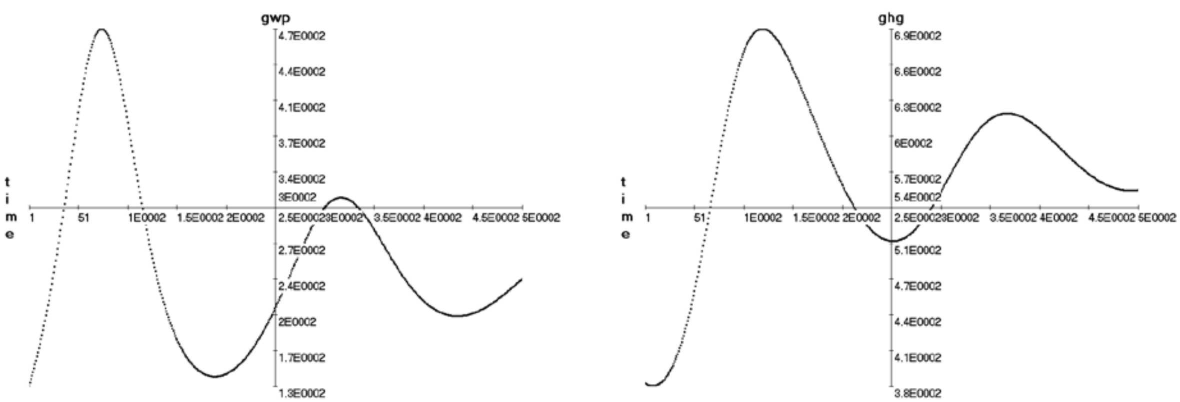
(1) $GHG(t+1) = (1-0.0083)GHG(t) + 0.024\times GWP(t)$.

(2) $GWP(t+1) = [1+ 0.03 - D(T(GHG(t)))]GWP(t)$.

If D were linear in GHG, this would be a simple Lotka Volterra type system. With *cs* as the climate sensitivity and 280 ppm the pre-industrial level of greenhouse gases, equilibrium temperature follows $T(GHG(t)) = cs\times \ln(GHG(t)/280)/\ln(2)$. Adopting Weitzman's (2010) notion of a "death temperature" of 18°C we write damages as $D(GHG)(t) = (T/18)^2$. Anthropogenic greenhouse gases increase with production; if GWP(t) were constant, they would increase to a constant $0.024\times GWP/0.0083$ However, as GWP increases, GHGs and temperature keep rising as well, lowering the growth rate of GWP. When $D > 0.03$, GWP starts decreasing. Eventually $0.024\times GWP < 0.0083$, and then greenhouse gases start decreasing, reducing damages to a point where production can start growing again. Figure 2 shows

GWP and GHG as functions of time out to 500 yrs, with all variables at their nominal values. GWP collapses. Greenhouse gases also collapse, but not to their initial level; hence the next upswing in GWP is attenuated. A steady state is eventually reached after some 1,500 years. This is not offered as a plausible model, its role is to spotlight the fundamental modeling assumptions. Evidently, different ways of modeling the impact of climate change damages give qualitatively different predictions, and steady state values may not be relevant for current policy choices. Neither theoretical nor empirical evidence exclude the Lotka Volterra type of interaction between damages and production presented here. A credible uncertainty analysis should fold in this and other possibilities, which brings us to the next point of examining a range of future conditions for a given policy choice.

Figure 3: The impact of climate damages on GWP (left) and greenhouse gases (right)

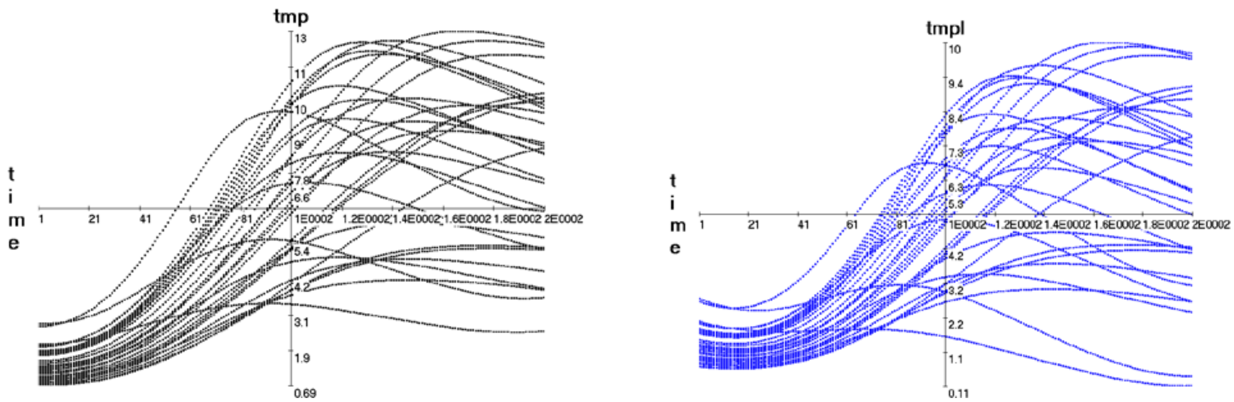


Structured Expert Judgment for Quantifying Uncertainties

Uncertainty analysis with climate models must be informed by the broad community of climate experts - not simply the intuitions or proclivities of modelers - through a process of structured expert judgment. Experience teaches that independent experts will not necessarily buy into the models whose parameter uncertainties they are asked to quantify. Hence, experts must be queried about observable phenomena, results of thought-experiments if you will, and their uncertainty over these phenomena must be ‘pulled back’ onto the parameters of the model in question. This process is analogous to the process by which model parameters would be estimated from data, if there were data. The new wrinkle is that data are replaced by experts’ uncertainty distributions on the results of possible, but not actual, measurements. The ‘pull back’ process is called probabilistic inversion, and has been developed and applied extensively in uncertainty analysis over the last two decades (see Cooke and Kelly 2010 and references therein). In general, an exact probabilistic inverse does not exist, and the degree to which a model enables a good approximation to the original distributions on observables forms an important aspect of model evaluation. Four features of the structured expert judgment approach deserve mention: (i) Experts are regarded as statistical hypotheses, and their statistical likelihood and informativeness are assessed by their performance on calibration questions from their field whose true values are known post hoc. (ii) Experts’ ability to give statistically accurate and informative assessments is found to vary considerably. (iii) Experts’ uncertainty assessments are combined using performance based weights. (iv) Dependence, either assessed directly by experts or induced by the probabilistic inversion operation, is a significant feature of an uncertainty analysis.

When uncertainty has been quantified in a traceable and defensible manner, an ensemble of possible futures for each policy choice may be generated. Figure 4 shows 30 Lotka Volterra temperature trajectories out to 200 years, with BAU emissions at 2.4% GWP (left) and stringent emissions at 1.5% of GWP (right); and using representative distributions for uncertain variables. Employing a value at risk management strategy, we would search for an emissions path optimizing consumption while holding the probability of exceeding a stipulated temperature threshold below a tolerable threshold.

Figure 4: Possible temperature trajectories under (left) emissions at 2.4%GWP and (right) emissions at 1.8% GWP (right)



These reflections challenge us to deploy risk management strategies on a global scale. We suggest this begin with (i) stress testing models, (ii) exploring alternative models, and (iii) quantifying uncertainty in such models via structured expert judgment. We are condemned to choose a climate policy without knowing all the relevant parameters, but we are not condemned to ignore the downside risks of our choices.

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

Sponsored by EPA United States Environmental Protection Agency; U.S. Department of Energy

November 18-19, 2010 Omni Shoreham Hotel, Washington, DC

Workshop Agenda

MODELING CLIMATE CHANGE IMPACTS AND ASSOCIATED ECONOMIC DAMAGES

November 18, 2010

Workshop Introduction

8:30 – 8:35 ***Welcome and Introductions***
Elizabeth Kopits, U.S. Environmental Protection Agency

8:35 – 9:00 ***Opening Remarks***
Bob Perciasepe, Deputy Administrator, U.S. Environmental Protection Agency
Steve Koonin, Under Secretary for Science, U.S. Department of Energy

9:00 – 9:25 ***Progress Toward a Social Cost of Carbon***
Michael Greenstone, Massachusetts Institute of Technology

Session 1: Overview of Existing Integrated Assessment Models
Moderator: Stephanie Waldhoff, U.S. Environmental Protection Agency

9:25 – 9:50 ***Overview of Integrated Assessment Models***
Jae Edmonds, Pacific Northwest National Laboratory

Models Used for the Development of Current USG SCC Values

9:50–10:15 ***DICE***
Steve Newbold, U.S. Environmental Protection Agency

10:15–10:40 ***PAGE***
Christopher Hope, University of Cambridge

10:40–10:55 ***Break***

10:55–11:20 ***FUND***
David Anthoff, University of California, Berkeley

Representation of Climate Impacts in other Integrated Assessment Models

11:20–11:45 ***GCAM*** (JGCRI – UMD/PNNL) ***and Development of iESM*** (PNNL/LBNL/ORNL)
Leon Clarke, Pacific Northwest National Laboratory

11:45–12:10 ***IGSM*** (MIT)
John Reilly, Massachusetts Institute of Technology

12:10–12:40 **Discussion**

12:40 – 1:40 ***Lunch (on your own; a list of nearby restaurants is provided in the registration packets)***

***Session 2**: Near-Term DOE and EPA Efforts*
Moderator: Ann Wolverton, U.S. Environmental Protection Agency

1:40 – 2:00 ***Proposed Impacts Knowledge Platform***
Bob Kopp, U.S. Department of Energy
Nisha Krishnan, Resources for the Future

2:00 – 2:20 ***Proposed Generalized Modeling Framework***
Alex Marten, U.S. Environmental Protection Agency

2:20 – 2:40 **Discussion**

***Session 3A**: Critical Modeling Issues in Assessment and Valuation of Climate Change Impacts*
Moderator: Ann Wolverton, U.S. Environmental Protection Agency

2:40 – 3:10 ***Sectoral and Regional Disaggregation and Interactions***
Ian Sue Wing, Boston University

3:10–3:20 ***Break***

3:20–3:50 ***Adaptation and Technological Change***
Ian Sue Wing, Boston University

3:50–4:20 ***Multi-century Scenario Development and Socio-Economic Uncertainty***
Brian O'Neill, National Center for Atmospheric Research

4:20–5:00 **Discussion**

November 19, 2010

Day 2 Introduction

8:30–8:40 ***Welcome; Recap of Day 1; Overview of Day 2***
Elizabeth Kopits, U.S. Environmental Protection Agency

Session 3B: Critical Modeling Issues in Assessment and Valuation of Climate Change Impacts (cont.)

Moderator: Bob Kopp, U.S. Department of Energy

8:40–9:10 ***Incorporation of Climate System Uncertainty into IAMs***
Gerard Roe, University of Washington

9:10–9:40 ***Extrapolation of Damage Estimates to High Temperatures: Damage Function Shapes***
Marty Weitzman, Harvard University

9:40–10:10 ***Earth System Tipping Points***
Tim Lenton, University of East Anglia

10:10–10:30 ***Break***

10:30–11:00 ***Potential Economic Catastrophes***
Michael Toman, World Bank

11:00–11:30 ***Nonmarket Impacts***
Michael Hanemann, University of California, Berkeley

11:30–12:30 **Discussion**

12:30–1:30 ***Lunch (on your own; a list of nearby restaurants is provided in the registration packets)***

Session 4: Implications for Climate Policy Analysis and Design

Moderator: Charles Griffiths, U.S. Environmental Protection Agency

1:30–2:00 ***Implications for Design and Benefit-Cost Analysis of Emission Reduction Policies***
Ray Kopp, Resources for the Future

2:00–2:30 ***Implications for Addressing Equity and Natural Capital Impacts***
Geoff Heal, Columbia University

2:30–3:00 ***Implications for Choice of Policy Targets for Cost-Effectiveness Analysis***
Nat Keohane, Environmental Defense Fund

3:00–3:10 ***Break***

3:10–3:40 ***Implications for Managing Climate Risks***
Roger Cooke, Resources for the Future

3:40–4:15 **Discussion**

Session 5*: *Workshop Wrap-up

4:15–4:30 ***Summary Comments by U.S. Department of Energy***
Rick Duke, Deputy Assistant Secretary for Climate Policy

4:30–4:45 ***Summary Comments by U.S. Environmental Protection Agency***
Al McGartland, Director of the National Center for Environmental Economics

Estimating the Social Cost of Carbon for the United States Government

Michael Greenstone
3M Professor of Environmental Economics
Massachusetts Institute of Technology
November 2010

The climate is a key ingredient in the earth's complex system that sustains human life and well being. According to the United Nation's Intergovernmental Panel on Climate Change (IPCC), the emissions of greenhouse gases (GHG) due to human activity, large the combustion of fossil fuels like coal, is "very likely" altering the earth's climate, most notably by increasing temperatures, precipitation levels and weather variability. Without coordinated policy around the globe, state of the art climate models predict that the mean temperature in the United States will increase by about 10.7° F by the end of the century (Deschenes and Greenstone 2010). Further, the distribution of daily temperatures is projected to increase in ways that pose serious challenges to well being; for example, the number of days per year where the typical American will experience a mean (average of the minimum and maximum) temperature that exceeds 90° F is projected to increase from the current 1.3 days to a 32.2 days (ibid). The especially troubling statistic is that the hottest days pose the greatest threat to human well being.

It appeared that the United States and possibly the major emitters were poised to come together to confront climate change by adopting a coordinated set of policies that could have included linked cap and trade systems. However, the failure of the United States Government to institute such a system and the non-binding commitments from the Copenhagen Accord seem to have placed the all at once solution to climate change out of reach for at least several years.

Instead, the United States and many other countries are likely to pursue a series of smaller policies all of which aim to reduce GHG emissions but individually have a marginal impact on atmospheric concentrations. These policies will appear in a wide variety of domains, ranging from subsidies for the installation of low carbon energy sources to regulations requiring energy efficiency standards in buildings, motor vehicles, and even vending machines to rebates for home insulation materials. Although many of these policies have other goals, their primary motivation is to reduce GHG emissions. However, these policies reduce GHG emissions at different rates and different costs.

In the presence of this heterogeneity and nearly limitless set of policies that reduce GHG emissions, how is government to set out a rational climate policy? The key step is to determine the monetized damages associated with an incremental increase in carbon emissions, which is referred to as the social cost of carbon (SCC).[1] It is intended to include (but is not limited to) changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services.[2] Monetized estimates of the economic damages associated with carbon dioxide emissions allows the social benefits of regulatory actions that are expected to reduce these emissions to be incorporated into cost-benefit analyses.[3] Indeed as the Environmental Protection Agency begins to regulate greenhouse gases under the Clean Air Act, the SCC can help to identify the regulations where the net benefits are positive.

The United States Government (USG) recently selected four SCC estimates for use in regulatory analyses and has been using them regularly since their release. For 2010, the central value is $21 per ton of CO2 equivalent emissions.[4] The USG also announced that it would conduct sensitivity analyses at $5, $35, and $65. The $21, $5, and $35 values are associated with discount rates of 3%, 2.5%, and 5%, reflecting that much of the damages from climate change are in the future. The $65 value aims to represent the higher-than-expected impacts from temperature change further out in the tails of the SCC distribution. In particular, it is the SCC value for the 95th percentile at a 3 percent discount rate. These SCC estimates also grow over time based on rates endogenously determined within each model. For instance, the central value increases to $24 per ton of CO_2 in 2015 and $26 per ton of CO_2 in 2020.

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[1] Under Executive Order 12866, agencies in the Executive branch of the U.S. Federal government are required, to the extent permitted by law, "to assess both the costs and the benefits of the intended regulation and, recognizing that some costs and benefits are difficult to quantify, propose or adopt a regulation only upon a reasoned determination that the benefits of the intended regulation justify its costs."

[2] All values of the SCC are presented as the cost per metric ton of CO_2 emissions.

[3] Most regulatory actions are expected to have small, or "marginal," impacts on cumulative global emissions, making the use of SCC an appropriate measure.

[4] All dollar values are expressed in 2007 dollars.

I was involved in the interagency process that selected these values for the SCC and this talk summarizes these efforts.[5] The process was initiated in 2009 and completed in February 2010. It aimed to develop a defensible, transparent, and economically rigorous way to value reductions in carbon dioxide emissions that result from actions across the Federal government. Specifically, the goal was to develop a range of SCC values in a way that used a defensible set of input assumptions, was grounded in the existing literature, and allowed key uncertainties and model differences to transparently and consistently inform the range of SCC estimates used in the rulemaking process.

The intent of this lecture is to explain the central role of the social cost of carbon in climate policy, to summarize the methodology and process used by the interagency working group to develop values, and to identify key gaps so that researchers can fill these gaps. Indeed, the interagency working group explicitly aimed the current set of SCC estimates to be updated as scientific and economic understanding advances.

[5] This process was convened by the Council of Economic Advisers and the Office of Management and Budget, with regular input from other offices within the Executive Office of the President, including the Council on Environmental Quality, National Economic Council, Office of Energy and Climate Change, and Office of Science and Technology Policy. Agencies that actively participated included the Environmental Protection Agency, and the Departments of Agriculture, Commerce, Energy, Transportation, and Treasury.

PROGRESS TOWARD A SOCIAL COST OF CARBON

Michael Greenstone
3M Professor of Environmental Economics
Massachusetts Institute of Technology

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

November 18, 2010

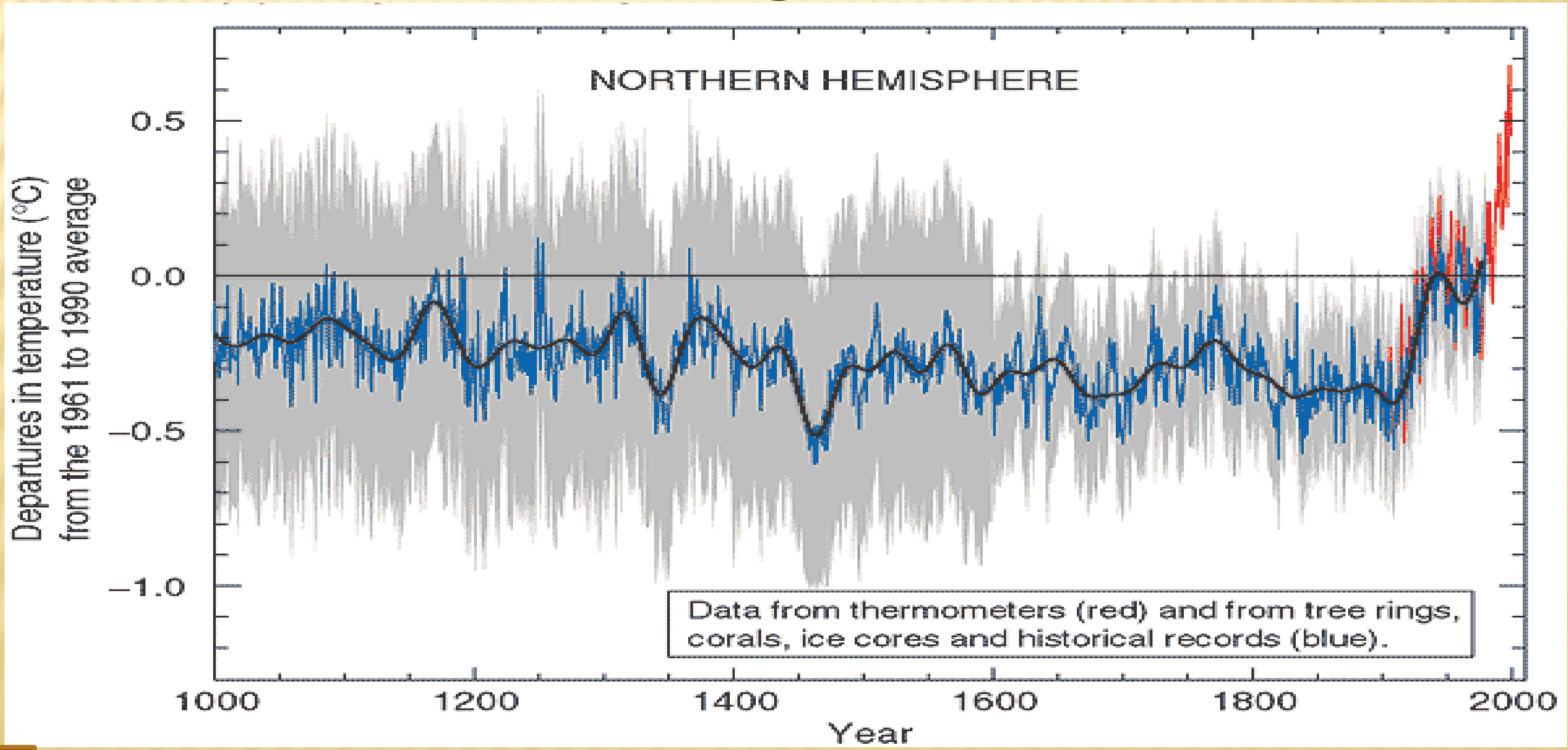
OUTLINE

I. Background & Motivation
II. Social Cost Of Carbon (SCC)
III. How is the SCC Calculated?
IV. Lifetime Damages of a Ton of CO_2 Emissions
V. Results
VI. Limitations
VII. Conclusions

I. BACKGROUND & MOTIVATION

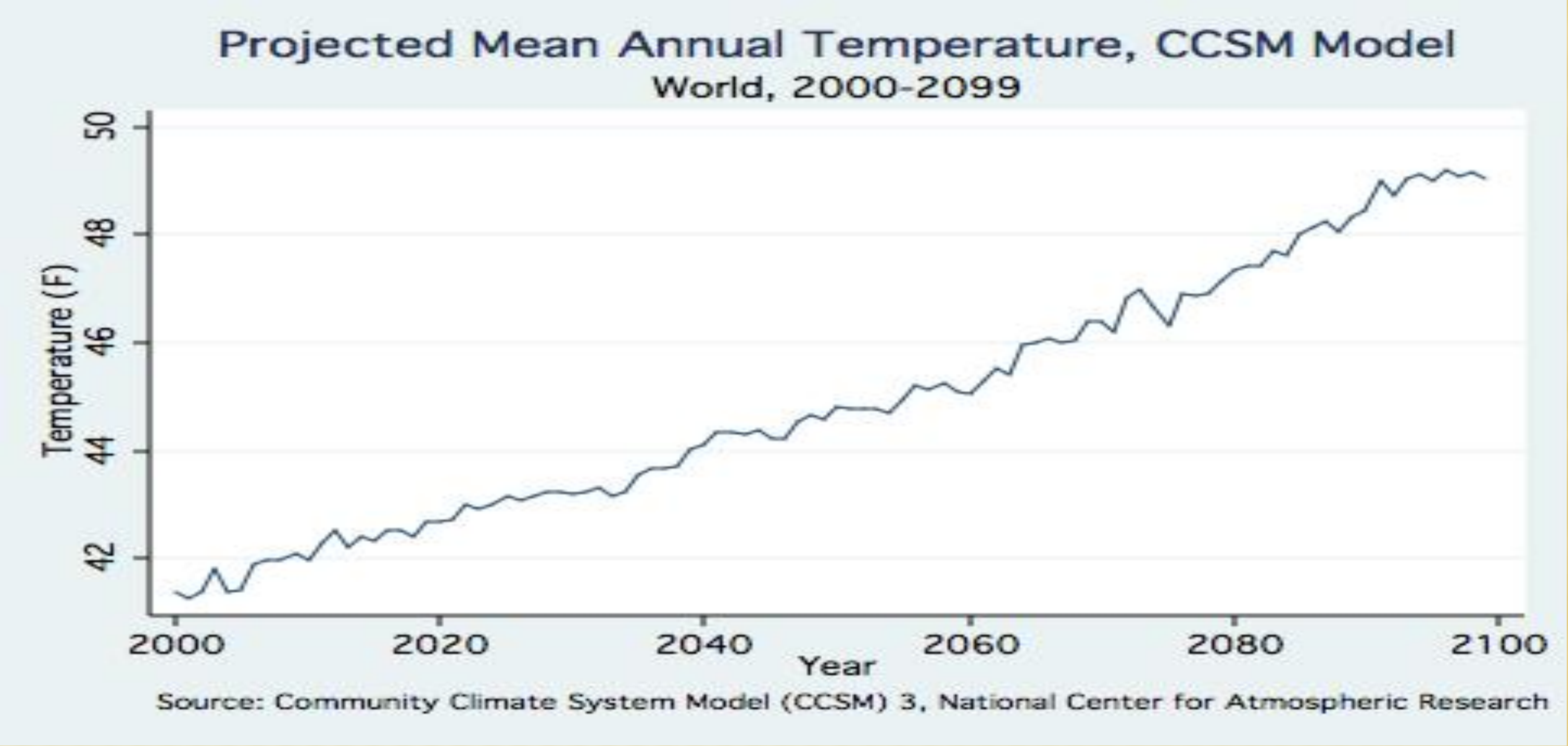
RISING TEMPERATURES

- Human-induced CO_2 emissions will likely cause temperature increases
- May have already begun

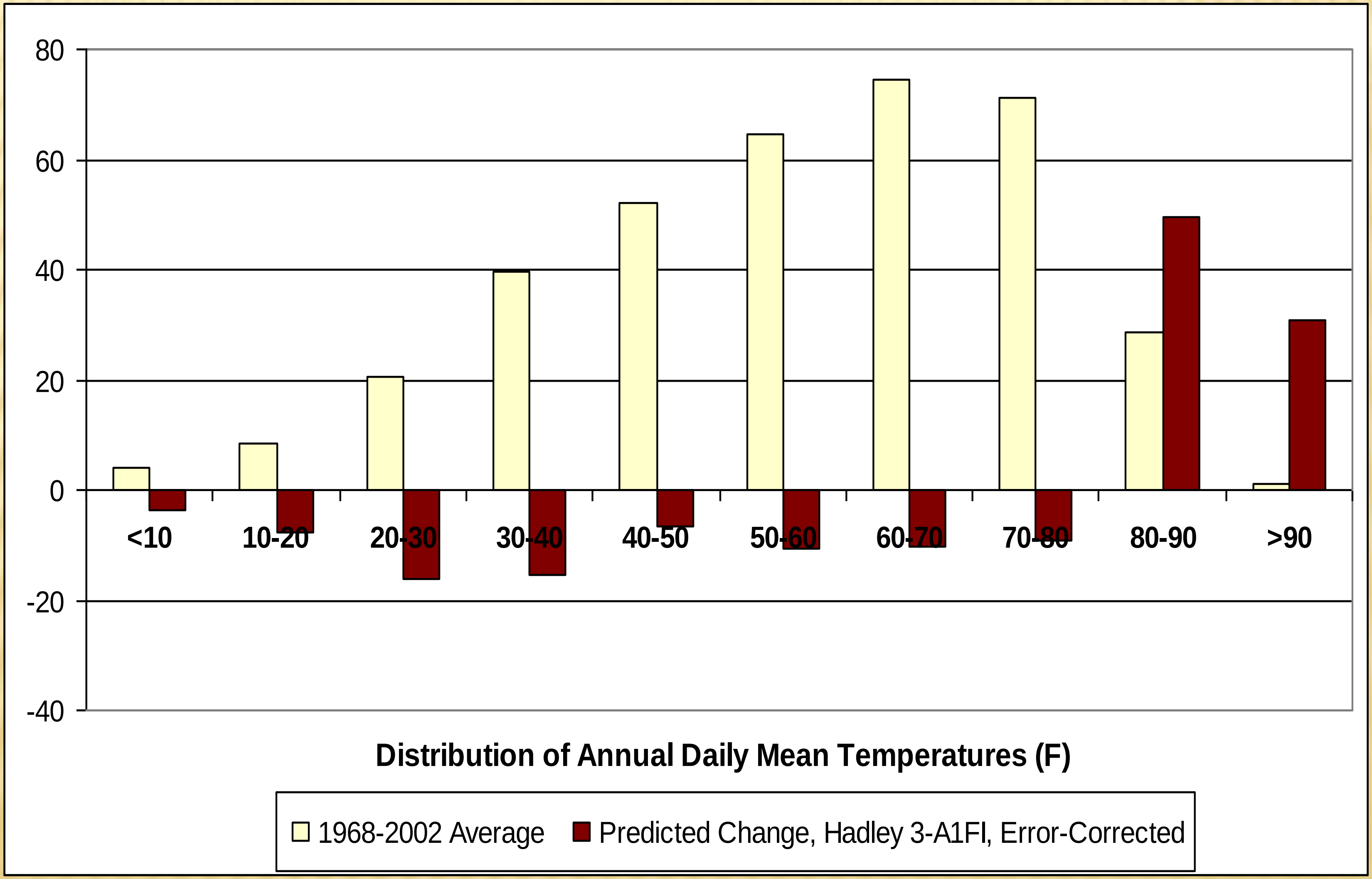


RISING TEMPERATURES

- Global temperatures projected to increase by 18% between 2000 and 2100



CURRENT AND PREDICTED CHANGE IN DISTRIBUTION OF TEMPERATURE FOR 2070-2099, UNITED STATES



U.S. LEGISLATION LANDSCAPE

- House passed Waxman-Markey cap-and-trade bill
- Senate declined to pursue legislation
- Best case in next several years:
  - Renewable electricity standards
  - More subsidies for nuclear power

CLEAN AIR ACT

- EPA has finalized a "tailoring" rule for Greenhouse Gases (GHG) under the Clean Air Act to take effect in January 2011
  - Set Rules that Govern Behavior of 900 Largest Sources
  - Statute Requires Use of "Best Available Control Technology"
  - Likely to Be Numerous Court Cases

CLEAN AIR ACT

- Likely Impact of Clean Air Act Regulations
  - Reduce GHG Emissions by 5-12% in 2020, relative to 2005. President Promised 17% in Copenhagen

CLEAN AIR ACT

- Will these Regulations have Net Benefits?
  - A regulatory impact analysis (RIA) will be required and informs the public of the relative costs and benefits of this mandate
  - Analyses will use the "social cost of carbon" to monetize the benefits stemming from CO_2 reduction

II. SOCIAL COST OF CARBON

A. DEFINITION

- SCC: monetized damages associated with an incremental increase in carbon emissions in a given year

- It includes but is not limited to changes in:
  - Net agricultural productivity
  - Human health
  - Property damages from increased flood risk
  - The value of ecosystem services

B. SCC IN ACTION

- Up-front Technology Costs and Social Benefits of EPA/DOT GHG Emissions Standards for Light-Duty Trucks 2010-2050 (NPV 3% Discount Rate and 2007 Dollars)

	2007 $s	
Social Benefits	$277.5	
Costs	-$345.9	
Net Benefits, without SCC	-$68.4	
Social Benefits of CO2 Reductions (Central Value)		
Total Net Benefits		

B. SCC IN ACTION

- Up-front Technology Costs and Social Benefits of EPA/DOT GHG Emissions Standards for Light-Duty Trucks 2010-2050 (NPV 3% Discount Rate and 2007 Dollars)

	2007 $s	
Social Benefits	$277.5	
Costs	-$345.9	
Net Benefits, without SCC	-$68.4	
Social Benefits of CO2 Reductions (Central Value)	$176.7	
Total Net Benefits	$108.3	

III. HOW IS THE SOCIAL COST OF CARBON CALCULATED?

ESTIMATING SCC

- A USG interagency working group developed a transparent and economically rigorous way to estimate SCC

- Now will Summarize Some of the Key Decisions and Results. (USG Plans to Revisit as Science Advances)

III. HOW IS SOCIAL COST OF CARBON CALCULATED

A. INTEGRATED ASSESSMENT MODELS

A. INTEGRATED ASSESSMENT MODELS (IAMS)

- IAMs combine Climate Processes, Economic Growth, and Feedbacks between the Climate and the Global Economy into a single model

- Specifically, IAM translate changes in CO_2 emissions into economic damages

1. Emissions
[assumptions about GDP and population growth]

2. Emissions → Atmospheric GHG Concentrations
[based on carbon cycle]

3. GHG Concentrations → Changes in Temperature
[assumptions about climate model and climate sensitivity]

4. Temperature → Economic Damages (market and non-market)
[assumptions about damage functions]

A. INTEGRATED ASSESSMENT MODELS (IAMS)

- Benefit of these Models is that they Answer Everything

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- Cost of Models is that they Answer Everything

A. INTEGRATED ASSESSMENT MODELS (IAMS)

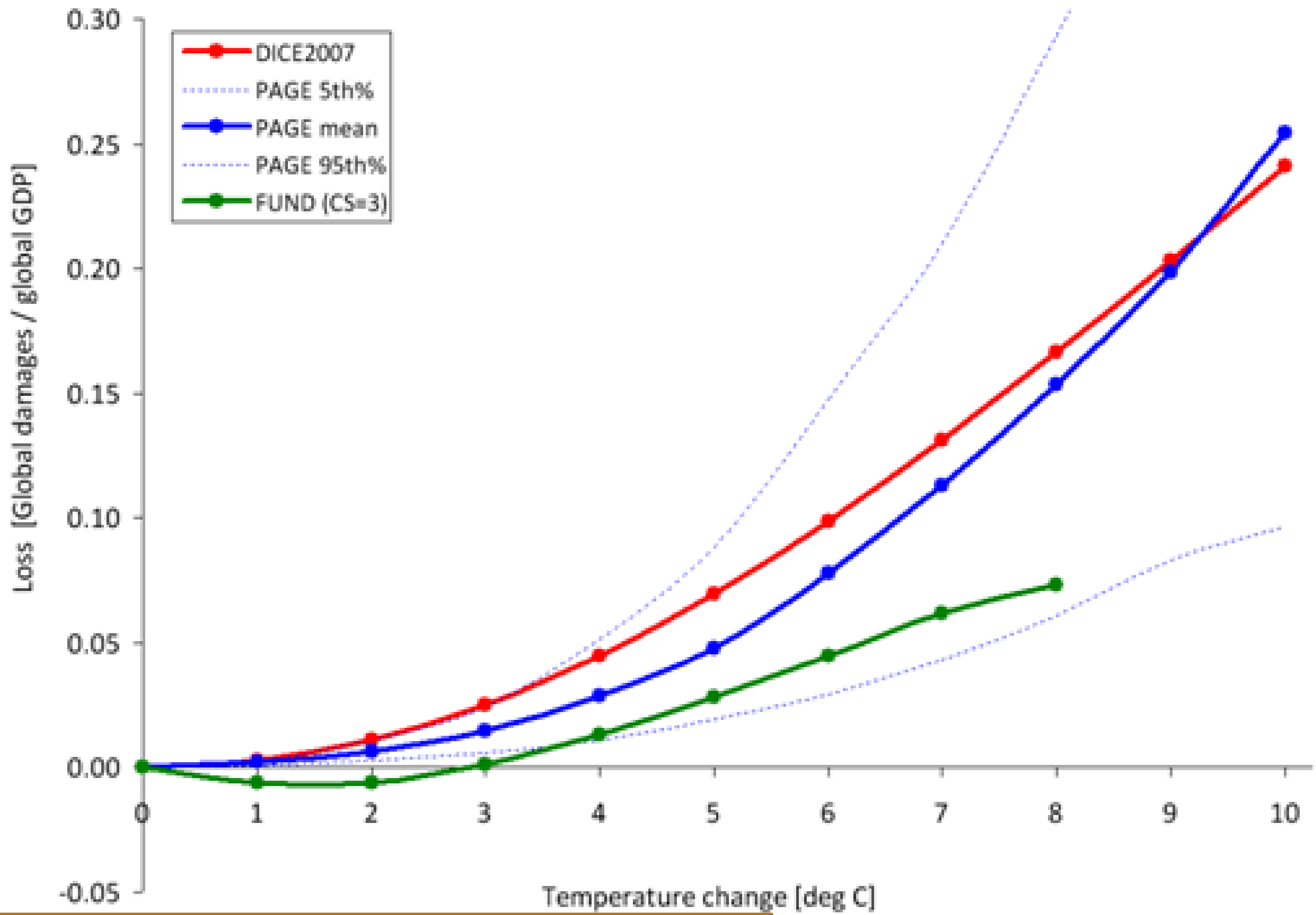
- Benefit of these Models is that they Answer Everything
- Cost of Models is that they Answer Everything
- Highly Dependent on Validity of Assumptions

A. INTEGRATED ASSESSMENT MODELS (IAMS)

- Relied on three commonly used IAM's to estimate SCC:
  - FUND (Richard Tol)
  - DICE (William Nordhaus)
  - PAGE (Chris Page)
- All 3 are frequently cited in the peer-reviewed literature and used in the IPCC assessment
- Each model is given equal weight to determine the SCC values

DAMAGE FUNCTIONS

Figure 1: Annual Consumption Loss as a Fraction of Global GDP in 2100 Due to an Increase in Annual Global Temperature in the DICE, FUND, and PAGE models



III. HOW IS THE SOCIAL COST OF CARBON CALCULATED?

B. ASSUMPTIONS

1. SOCIO-ECONOMIC & EMISSIONS TRAJECTORIES

- Socio-economic pathways are closely tied to climate damages
  - More and wealthier people tend to emit more GHG
  - Higher WTP to avoid climate disruptions
- For this reason, decisions necessary for several input parameters from present until 2100:
  - Global GDP
  - Global Population
  - Global CO_2 emissions

1. SOCIO-ECONOMIC & EMISSIONS TRAJECTORIES

- Relied on the Stanford Energy Modeling Forum exercise, EMF-22
  - Based on 4 of 10 models
  - Key advantage:
    - GDP, population and emission trajectories are internally consistent
  - Five trajectories selected:
    - 4 business-as-usual (BAU) paths
      - Correspond to 2100 concentrations of 612 – 889 ppm, reflecting differences in assumptions about cost of low carbon energy sources
    - 1 lower-than-BAU path
      - Achieves stabilization at 550 ppm in 2100

2. EQUILIBRIUM CLIMATE SENSITIVITY

- Equilibrium climate sensitivity (ECS): long-term increase in the annual global-average surface temperature due to a doubling of atmospheric CO_2 concentration relative to pre-industrial levels
  - Equivalent to the atmospheric CO_2 concentration stabilizing at about 550 parts per million (ppm)

2. EQUILIBRIUM CLIMATE SENSITIVITY

- According to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC):

  *We conclude that the global mean equilibrium warming for doubling CO_2 … is **likely to lie in the range 2°C to 4.5°C**, with a **most likely value of about 3 °C**. Equilibrium climate sensitivity is **very likely larger than 1.5 °C**…. For fundamental physical reasons as well as data limitations, **values substantially higher than 4.5 °C still cannot be excluded, but agreement with observations and proxy data is generally worse for those high values** than for values in the 2 °C to 4.5 °C range.*

2. EQUILIBRIUM CLIMATE SENSITIVITY

- Selected four candidate probability distributions and calibrated them to the IPCC statement:
  - Roe and Baker (2007)
  - Log-normal
  - Gamma
  - Weibull
- Calibration done by applying three constraints:
  - Median equal to 3°C
  - Two-thirds probability that ECS lies between 2 and 4.5°C
  - Zero probability that ECS is less than 0°C or greater than 10°C

2. EQUILIBRIUM CLIMATE SENSITIVITY

Table 1: Summary Statistics for Four Calibrated Climate Sensitivity Distributions

	Roe & Baker	Log-normal	Gamma	Weibull
Pr(ECS < 1.5°C)	0.013	0.050	0.070	0.102
Pr(2°C < ECS < 4.5°C)	0.667	0.667	0.667	0.667
5th percentile	1.72	1.49	1.37	1.13
Median	3.00	3.00	3.00	3.00
Mean	3.50	3.28	3.19	3.07
95th percentile	7.14	5.97	5.59	5.17

2. EQUILIBRIUM CLIMATE SENSITIVITY

- Selected the Roe and Baker distribution:
  - Only distribution based on a theoretical understanding of the response of the climate system to increased GHG concentrations
  - Most consistent with IPCC judgments regarding climate sensitivity:
    - "Values substantially higher than 4.5°C still cannot be excluded"
    - ECS "is very likely larger than 1.5°C"

3. GLOBAL OR DOMESTIC DAMAGES

- Current OMB guidance says Domestic Perspective is Mandatory and International Perspective is Optional

- Determined that a Global Measure of the Benefits from Reducing U.S. Emissions is Preferable:
  - Global Externality. Emissions in U.S. Cause Damages Around the World
  - The U.S. cannot mitigate climate change by itself
  - Decided against equity weighting that would place a greater weight on losses in poor countries
  - NB: Best available evidence is that US damages are 5-15% of global damges.

IV. LIFETIME DAMAGES OF A TON OF GHG EMISSIONS

A. LONG RUN DAMAGES

- Half Life of a Ton of CO_2 Emitted is 100 Years
- Ton of Emissions Today will Affect Temperatures and Damages for a Long Period
- Net Present Value of Damage due to Ton of Emissions Today Equals the Sum of the Discounted Value of the Damages Each Year Until It Has Disappeared from Atmosphere
  - The Choice of Discount Rate is a Key Factor

B. DISCOUNT RATES

- Choice of a discount rate, especially over long periods of time, raises difficult questions
- USG traditionally employs constant discount rates of both 3 percent and 7 percent

SELECTED DISCOUNT RATES

- In light of the above considerations, USG used three discount rates:
  - Low Value: 2.5 percent
    - Interest rates are highly uncertain over time
    - If climate investments are negatively correlated with market returns
    - Incorporates normative objections to rates of 3 percent or higher
  - Central Value: 3 percent
    - Consistent with estimates in the literature and OMB's guidelines for the consumption rate of interest
    - Roughly corresponds to the after-tax riskless rate
  - High Value: 5 percent
    - If climate investments are positively correlated with market returns
    - May be justified by the high interest rates many consumers use to smooth consumption
- Approach is largely descriptive and uses constant discount rates, but incorporates some key prescriptive concerns

C. PUTTING IT ALL TOGETHER

- Running the models produces 45 separate distributions of the SCC for a given year
  - (3 models) x (5 socioeconomic scenarios) x (1 climate sensitivity distribution) x (3 discount rates)
- The distributions from each of the models and scenarios are averaged together for each year
  - Produces three separate probability distributions for SCC in a given year, one for each discount rate

C. PUTTING IT ALL TOGETHER

For each IAM, here are steps for calculating the SCC:

1. Input the path of emissions, GDP, and population and calculate the temperature effects and (consumption-equivalent) damages in each year resulting from this baseline path of emissions.

2. Add an additional unit of carbon emissions in year *t* and recalculate the temperature effects and damages expected in all years beyond *t* resulting from this adjusted path of emissions.

3. Subtract the damages computed in step 1 from those in step 2 in each year.

4. Discount the resulting path of marginal damages back to the year of emissions using the agreed upon fixed discount rates and calculate the SCC as the net present value of the discounted path of damages.

V. RESULTS

OVERALL ESTIMATES

- USG selected four SCC estimates for use in regulatory analyses
  - In 2010, these estimates are \$5, \$21, \$35 & \$65 (in 2007 US\$)
  - First three estimates are the average SCC across 3 models & 5 emissions scenarios for 3 distinct discount rates
  - The fourth value represents higher-than-expected impacts
    - Use the SCC value for the 95th percentile at a 3 percent discount rate
  - The \$21 estimate associated with a 3% discount rate is the central value

HETEROGENEITY BY MODEL AND DISCOUNT RATE

Table 3: Disaggregated Social Cost of CO_2 Values by Model, Socio-Economic Trajectory, and Discount Rate for 2010 (in 2007 dollars)

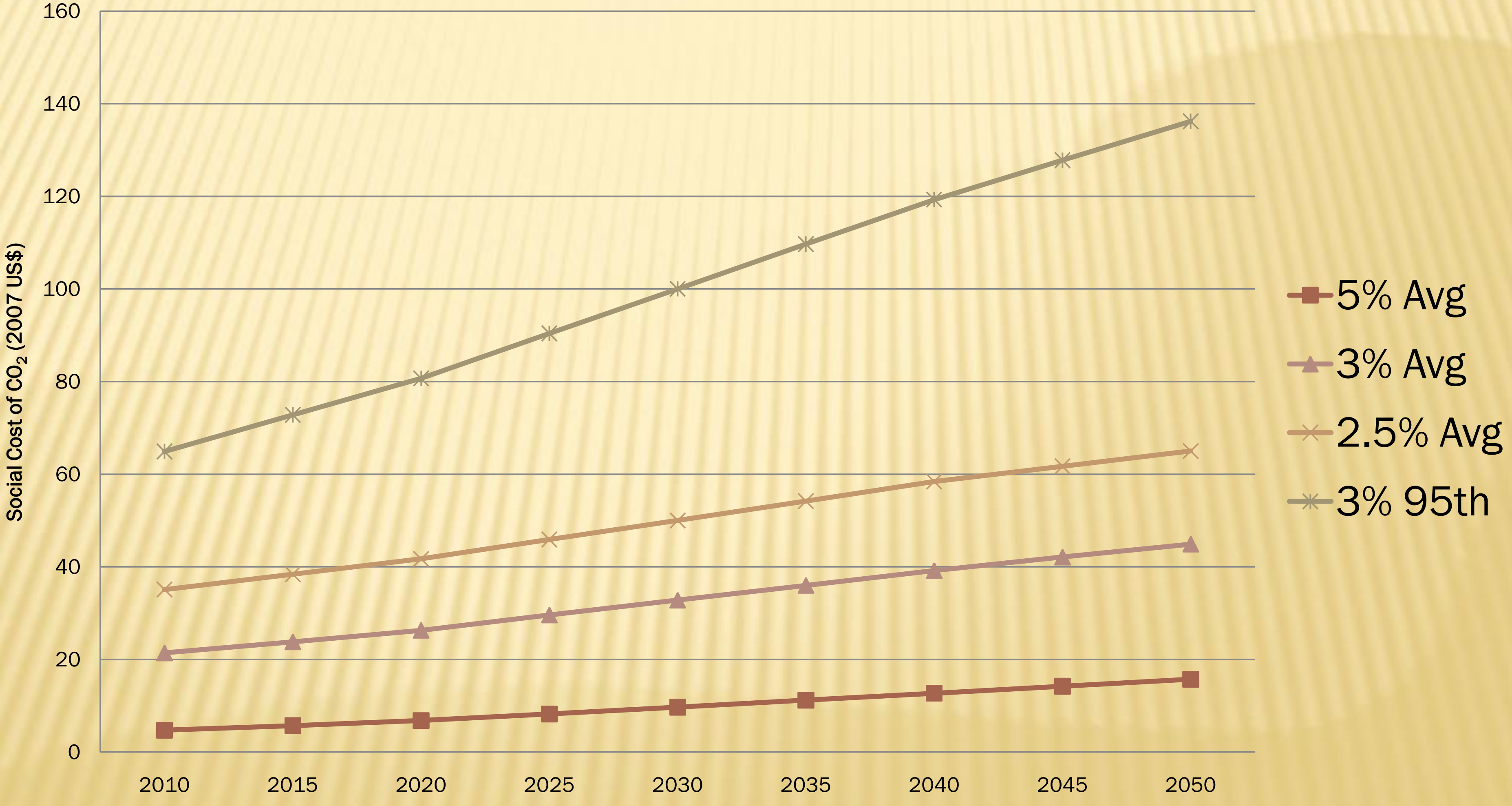
	Discount rate:	**5%**	**3%**	**2.5%**	**3%**
Model	*Scenario*	Avg	Avg	Avg	95th
DICE	IMAGE	10.8	35.8	54.2	70.8
	MERGE	7.5	22.0	31.6	42.1
	Message	9.8	29.8	43.5	58.6
	MiniCAM	8.6	28.8	44.4	57.9
	550 Average	8.2	24.9	37.4	50.8
PAGE	IMAGE	8.3	39.5	65.5	142.4
	MERGE	5.2	22.3	34.6	82.4
	Message	7.2	30.3	49.2	115.6
	MiniCAM	6.4	31.8	54.7	115.4
	550 Average	5.5	25.4	42.9	104.7
FUND	IMAGE	-1.3	8.2	19.3	39.7
	MERGE	-0.3	8.0	14.8	41.3
	Message	-1.9	3.6	8.8	32.1
	MiniCAM	-0.6	10.2	22.2	42.6
	550 Average	-2.7	-0.2	3.0	19.4

DISCUSSION

- Higher discount rates result in lower SCC values, and vice versa
- There are clear differences in the SCC estimated across the three main models
  - FUND produces the lowest estimates
  - PAGE produces the highest estimates
- Results match up fairly well with model estimates in the existing literature
- The SCC increases over time
  - Physical and economic systems will become more stressed

RESULTS OVER TIME

Figure 3: Social Cost of CO_2, 2010 – 2050 (in 2007 dollars)



VI. CONCLUSIONS & DIRECTIONS FOR UPDATING THE SCC

CONCLUSIONS

- The SCC offers a way to measure the economic value of emissions reductions
- The use of the SCC to guide GHG regulations under the Clean Air Act offers the possibility of achieving regulations where the benefits exceed the costs

DIRECTIONS FOR IMPROVEMENTS

- Key areas for future research and advances in calculation of SCC include:
  - Improvements in how IAM's capture catastrophic impacts
  - More attention to how predicted physical impacts translate into economic damages
  - Interactions between inter-sector and inter-regional impacts (e.g., conflict)
  - More complete treatment of adaptation and technological changes
  - Potential Incorporation of Risk Aversion
  - A methodology for valuing reductions in other GHG's

Overview of Integrated Assessment Models

Jae Edmonds and Kate Calvin

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

November 18, 2010

Washington, DC

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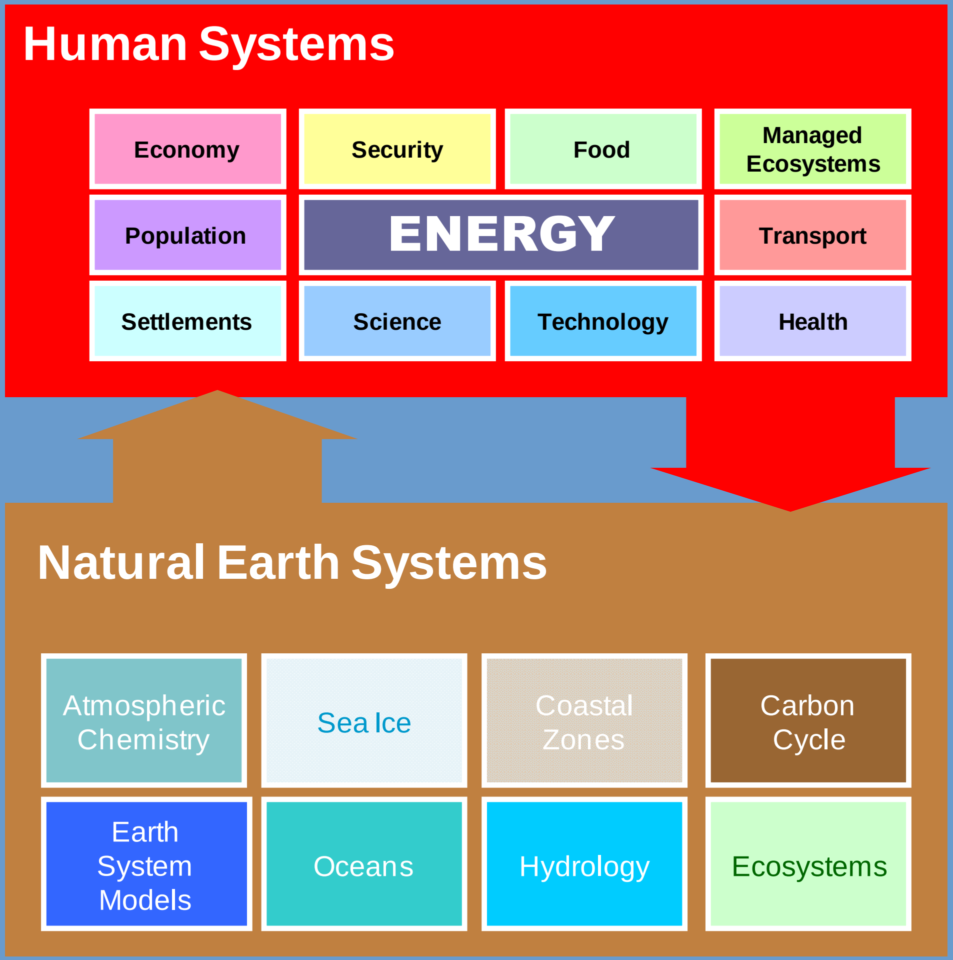
What is an Integrated Assessment Model (IAM)?

IAMs integrate human and natural Earth system climate science.

- IAMs provide insights that would be otherwise unavailable from disciplinary research.
- IAMs capture interactions between complex and highly nonlinear systems.
- IAMs provide natural science researchers with information about human systems such as GHG emissions, land use and land cover.

IAMs provide important, science-based decision support tools.

- IAMs support national, international, regional, and private-sector decisions.



IAMs Are Strategic in Nature

- IAMs were designed to provide strategic insights.

- IAMs were never designed to model the very fine details, e.g.
  - Electrical grid operation
  - Daily oil market price paths.

- IAMs are analogous to climate models in that sense.
  - Climate models don't forecast weather
  - They were designed to describe the determinants of 30-year moving averages of weather.

- IAMs also span a wide range of models with highly varied levels of spatial and temporal resolution.

Example of an IA insight: Sulfur & Land use

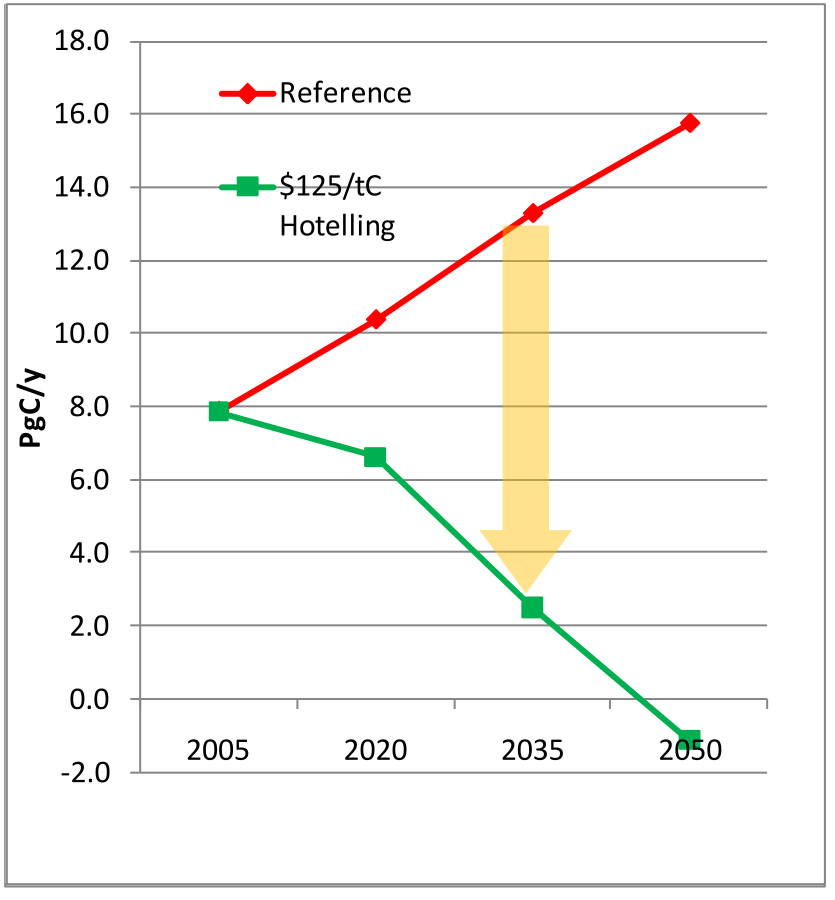
- Carbon tax cases can have higher radiative forcing than non-control scenarios.
  - Sulfur
  - Land-use change emissions

- I don’t have the original figure because it predates the age of PowerPoint.

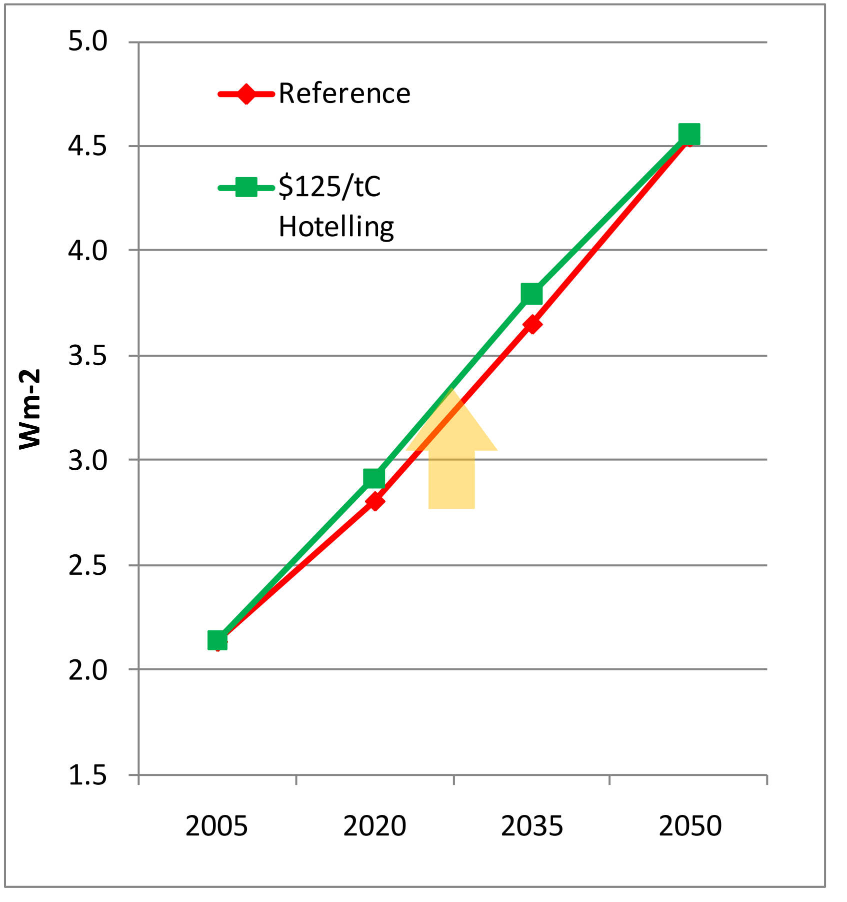
Example of an IA insight: Sulfur & Land use

- Consider a reference scenario, e.g. reference to GCAM RCP 4.5, and a scenario in which fossil fuel and industrial carbon is taxed.

Fossil Fuel & Industrial Carbon Emissions



Total Anthropogenic Radiative Forcing



- Radiative Forcing goes up prior to 2050 because of the sulfur aerosol and indirect land-use effects.

"HORSES FOR COURSES"

—JAKE JACOBY

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IAMs are a diverse set of tools

- The diversity of IAMs is a reflection of the diversity of problems for which the models were designed to address.
  - What is the optimal climate policy?
  - Implications of policy regimes for technology choice?
  - How do policy, energy, the economy, land use and terrestrial carbon cycle interact?
- IAMs are evolving to address new questions
  - How will emissions mitigation and climate impacts interact?
- The bigger the question, the more aggregated the model.

THE HIGHLY AGGREGATED IA MODELS

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Three BIG question models: DICE, FUND & PAGE

- As far as I can remember, this line of investigation begins with a series of discussion papers written by Bill Nordhaus in 1989 and 1990 leading to the DICE model.

- These models are characterized by high levels of **aggregation** and **comprehensiveness**.
  - Typically come in 3 parts.
    - Emissions
    - Natural Earth systems (atmospheric composition & climate change)
    - Climate Damages
  - RICE (the regional version of DICE) is ~17 equations
  - For comparison, GCAM is ~110,000 lines of code

Sources of Information

- Highly aggregated IAMs face the problem of establishing parameter values for the three major components—emissions, natural Earth systems, and climate damages.
- Most highly aggregated IAMs summarize information gleaned from other, more detailed models or from off-line research.
  - The relationship between the more highly resolved IAMs and the highly aggregated IAMs is similar in nature to the relationship between the Earth system models of intermediate complexity (EMICs) and the high resolution Earth system models (ESMs).
  - But the highly aggregated IAMs also derive information from other research domains, most notably the Impacts, adaptation and vulnerability (IAV) community.
  - (Climate research can be divided into IAV, IAM, and atmosphere-climate modeling domains.)

The highly aggregated IAMs are often used for the purpose of comparing the costs and benefits of policy intervention. This introduces several additional issues.

1. How to compare non-market damages?
   - Value of a human life—just ask David Pearce.
   - Value of unmanaged ecosystems.
   - While these problems are amenable to economic analysis, actual values are vigorously debated.
2. How to include interaction effects?
   - Across sectors—agriculture, energy and water
   - Mitigation and adaptation—who gets the land?
   - Land-use change from mitigation and adaptation affect climate?
3. How to compare across time—and not just one week or year to the next, but across multiple generations.

3. For the US, how to compare across space—should damages in distant lands be weighted as heavily as damages at home?

4. The tails of the distribution
   - Climate change potentially pushes the Earth system into regimes that have not been observed for millions of years.
     - And, even then big things are different, e.g. the placement of the continents.
   - Extreme and catastrophic events are possible.
     - Both events that might be imagined—e.g. rapid destabilization of clathrate zones, and.
     - Events that have not yet been imagined—the rapid emergence of the ozone hole was the consequence of heterogeneous chemistry that was not in the models until after the hole needed to be explained.
     - What is the proper weight to give to such events?

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THE HIGHER RESOLUTION IA MODELS

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The Higher Resolution IA Models Address Different Problems

- Higher resolution IAMs address questions associated with the details of the interactions between human and natural Earth systems.
  - The high resolution IAM economies are more disaggregated;
  - The high resolution IAM energy system technologies are highly varied;
  - Land use and land cover strongly interact with the economy, energy systems, and natural terrestrial processes.

- The higher resolution IAMs tend to focus on outputs in their natural units.
  - How many new nuclear builds?
  - How many Pg of CO_2 in geologic repositories?
  - What impact will climate change have on the price of wheat?

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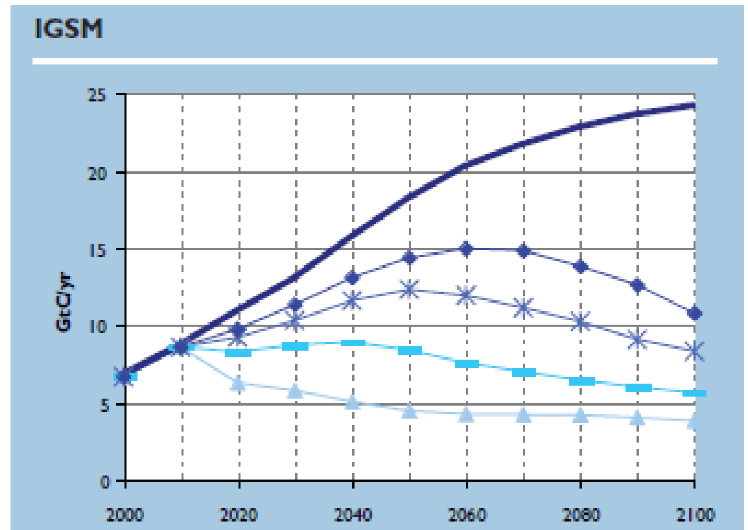
Cost effectiveness

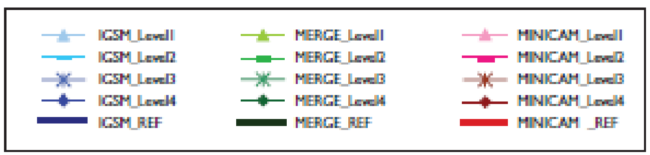
- The higher resolution IA models have focused on cost-effectiveness
  - What is the best way to stabilize CO_2 concentrations?
  - What is the best way to limit global mean surface temperature (GMST) not to exceed 2 degrees?
- Rich Richels' classic slide

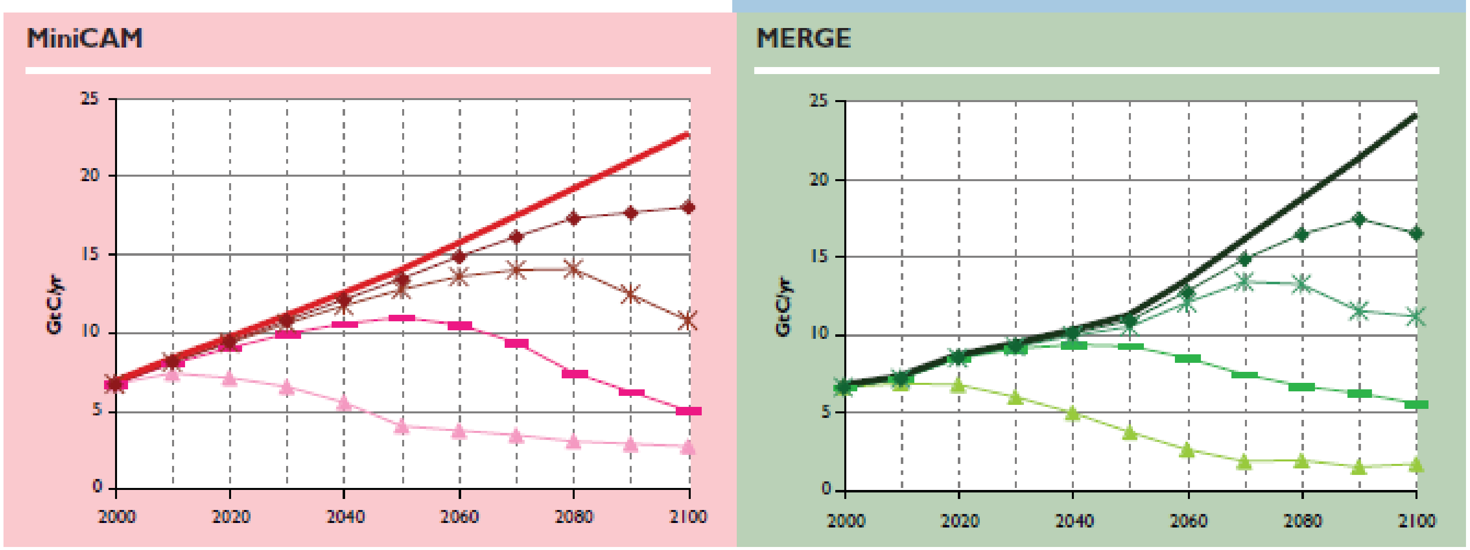
This is a cost-effectiveness study, NOT a cost-benefit study!!!

Cost effectiveness—SAP 2.1a

Figure TS.10 Global Emissions of CO_2 from Fossil and other Industrial Sources Across Scenarios (GtC/yr). The tighter the constraint on radiative forcing, the faster carbon emissions must decline from those in the reference scenarios. This is because the stabilization level defines a long-term carbon budget; that is, the remaining amount of carbon that can be emitted in the future. The gradual deflection of the emissions from the reference reflects the assumption of when flexibility, with carbon prices rising gradually. Under the most stringent radiative forcing stabilization levels, CO_2 emissions begin to decline immediately or within a matter of decades. Under less stringent radiative forcing stabilization levels, CO_2 emissions do not peak until late in the century or beyond, and they are 1½ to over 2½ times today's levels in 2100.







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Cost effectiveness

- Because the higher resolution IA models have focused on cost-effectiveness, they haven't had to worry that much about the problems of impacts, and impact valuation. For example,
  - They haven't worried about the tails of the distribution—they simply take the goal of limiting GMST to 2 degrees.
  - Policy-technology interactions have loomed large.
  - Discounting has been a lesser issue.
  - Enumerating a complete set of atmosphere-climate impacts has not been critical.
- That situation is changing as the higher resolution IA models focus more on impacts.

- The higher resolution of these models mean that interactions between sectors, regions, mitigation, adaptation, and climate can begin to be studied.

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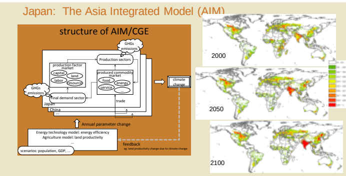
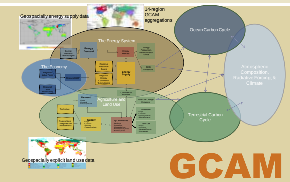
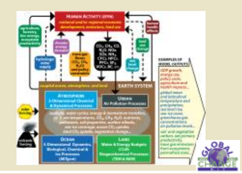
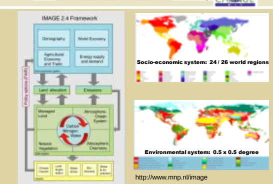
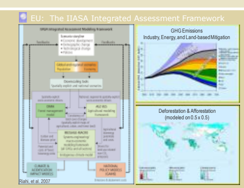
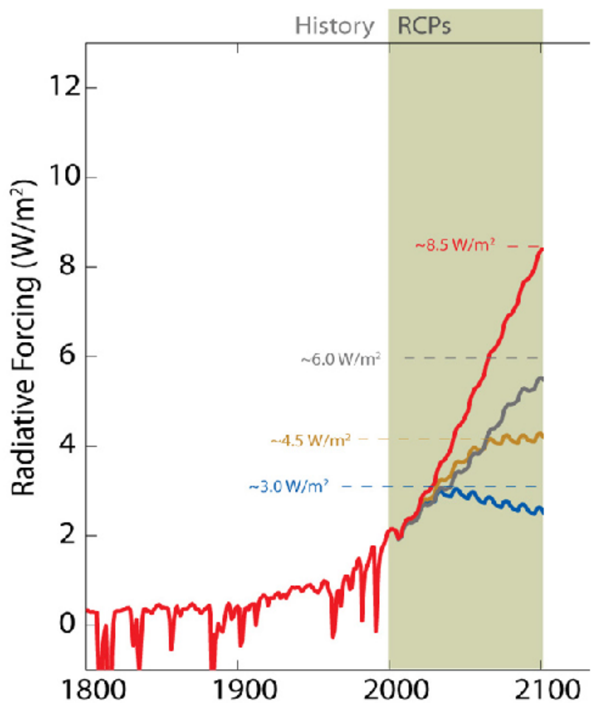
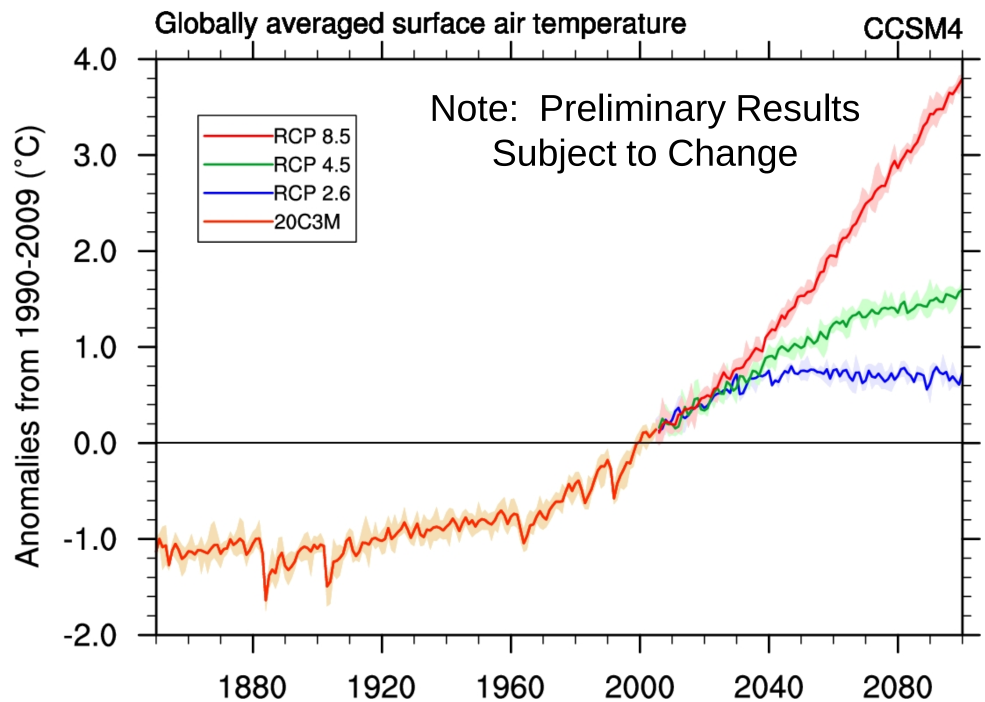
Higher Resolution Integrated Assessment Models are developed by interdisciplinary teams.

Model	Home Institution	
AIM Asia Integrated Model	National Institutes for Environmental Studies, Tsukuba Japan	
GCAM Global Change Assessment Model	Joint Global Change Research Institute, PNNL, College Park, MD	
IGSM Integrated Global System Model	Joint Program, MIT, Cambridge, MA	
IMAGE The Integrated Model to Assess the Global Environment	PBL Netherlands Environmental Assessment Agency, Bildhoven, The Netherlands	
MERGE Model for Evaluating the Regional and Global Effects of GHG Reduction Policies	Electric Power Research Institute, Palo Alto, CA	
MESSAGE Model for Energy Supply Strategy Alternatives and their General Environmental Impact	International Institute for Applied Systems Analysis; Laxenburg, Austria	

Higher resolution IAMs have provided atmosphere & climate models with both emissions and LULC trajectories

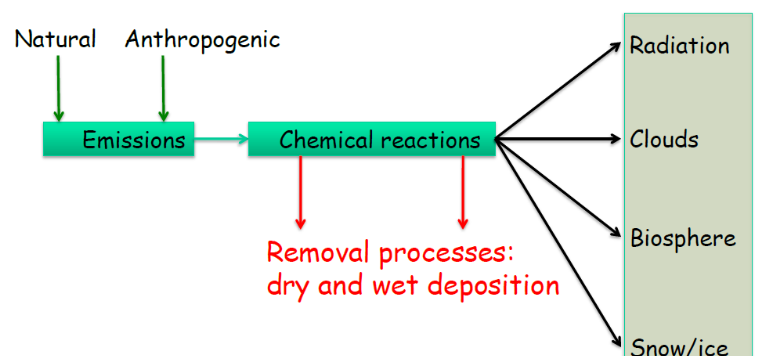
Emissions → Atmosphere → Climate





GHG Emissions and Concentrations from IAMs

- Greenhouse gases: CO_2, CH_4, N_2O, CFCs, HFC's, PFC's, SF_6
- Emissions of chemically active gases: CO, NO_x, NH_3, VOCs
- Derived GHG's: tropospheric O_3
- Emissions of aerosols: SO_2, Black Carbon (BC), Organic Carbon (OC)
- Land use and land cover

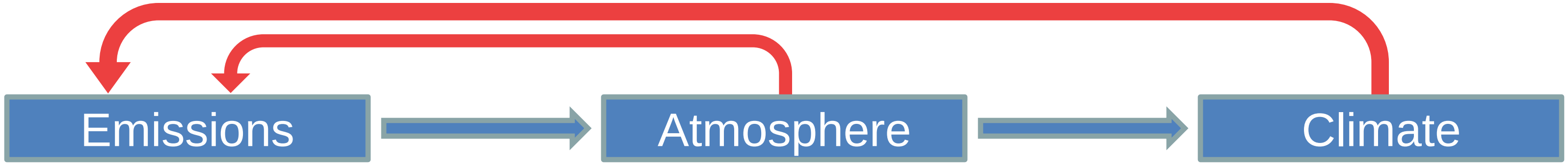


Thanks to Warren Washington for CCSM4 preliminary results.

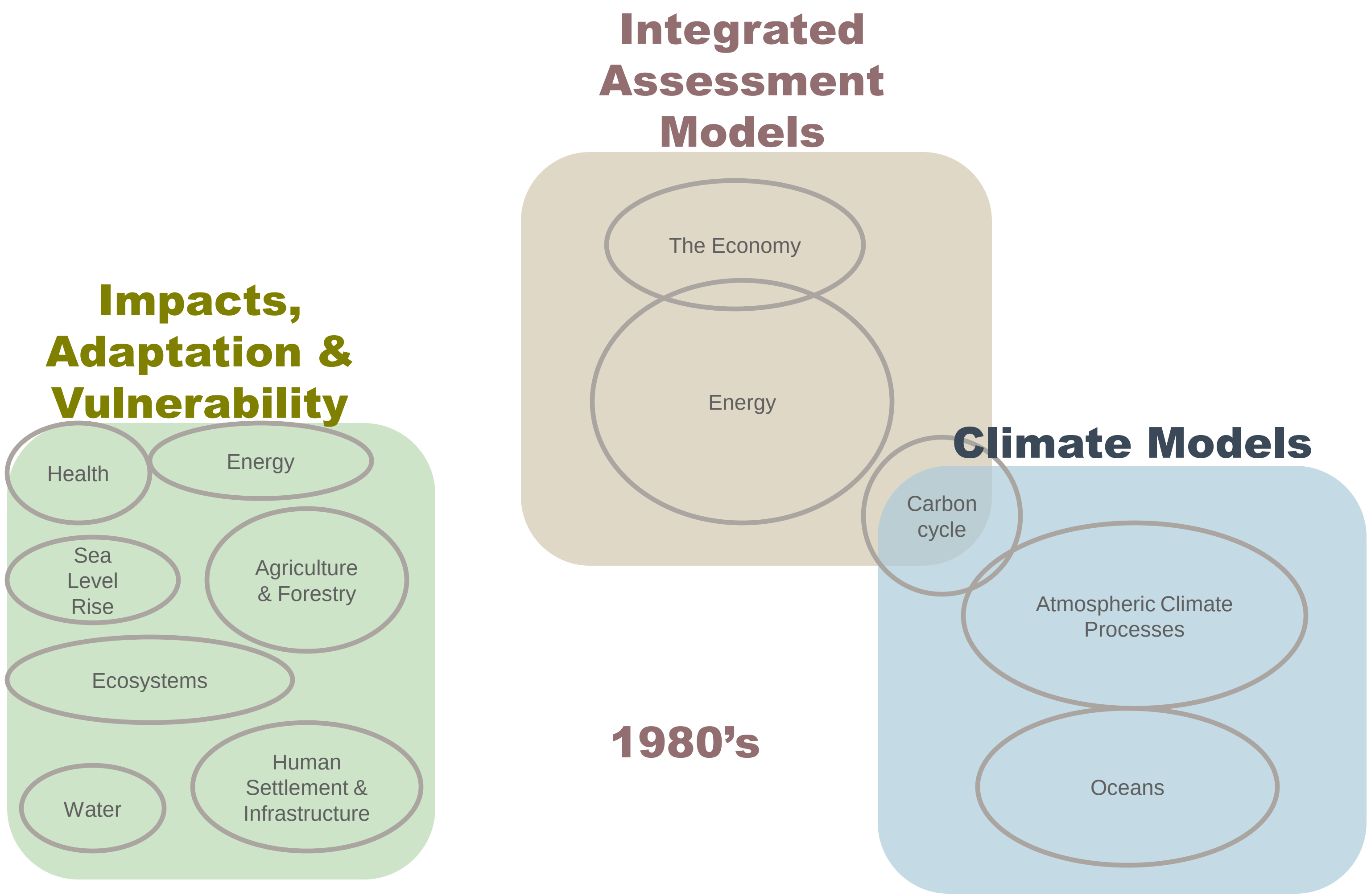
The iESM

- ***Models that integrate state of the art human Earth system models (taken from IAMs) with natural Earth system models (ESMs) are being actively developed.***

- ***The iESMs will provide feedbacks from atmosphere, oceans, and climate on terrestrial systems.*** E.g. climate and atmospheric composition feedbacks on crop yields, energy demands, bioenergy prices and climate mitigation.



Growing Overlap in Research Domains



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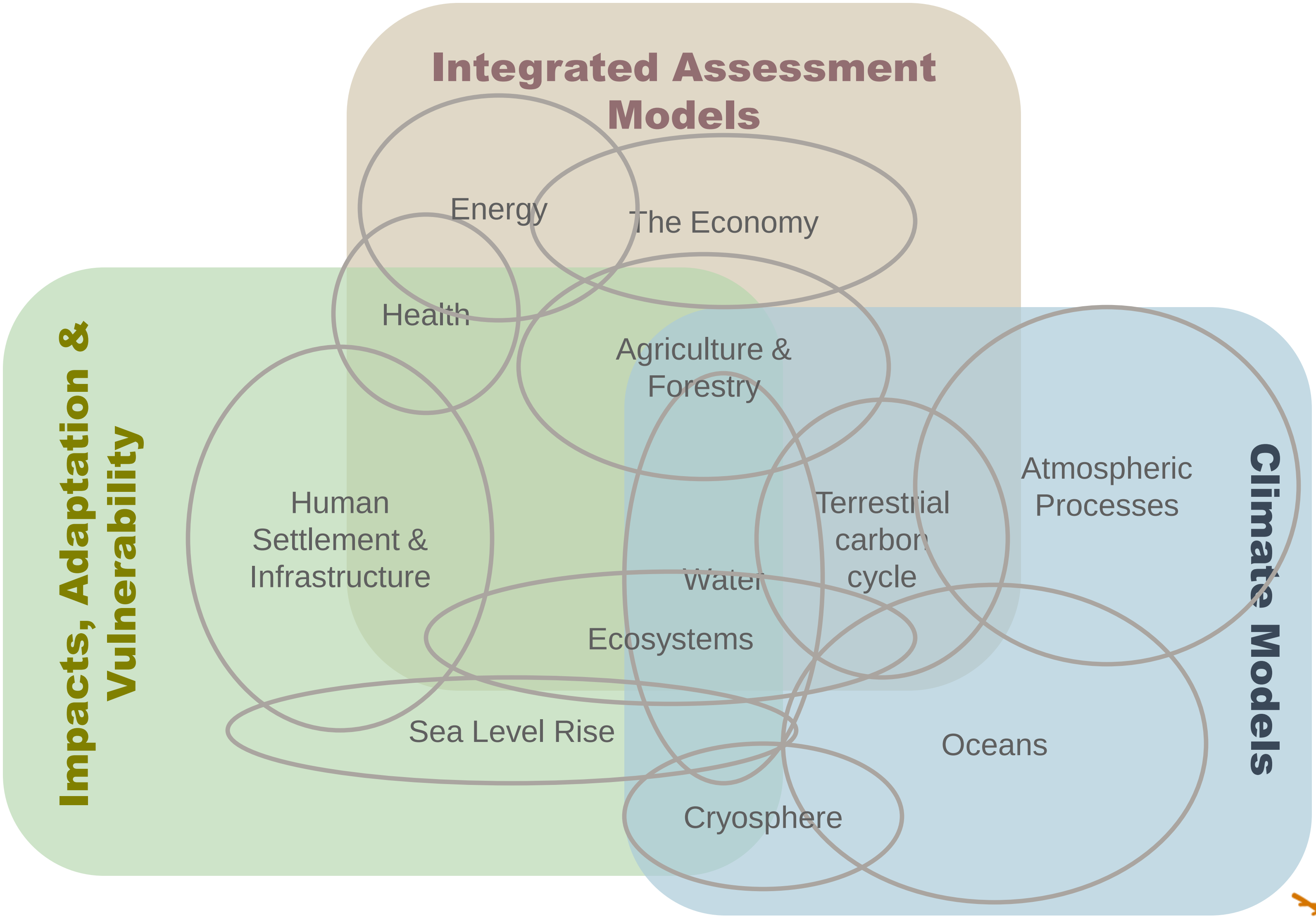
Where IAMs Are Headed



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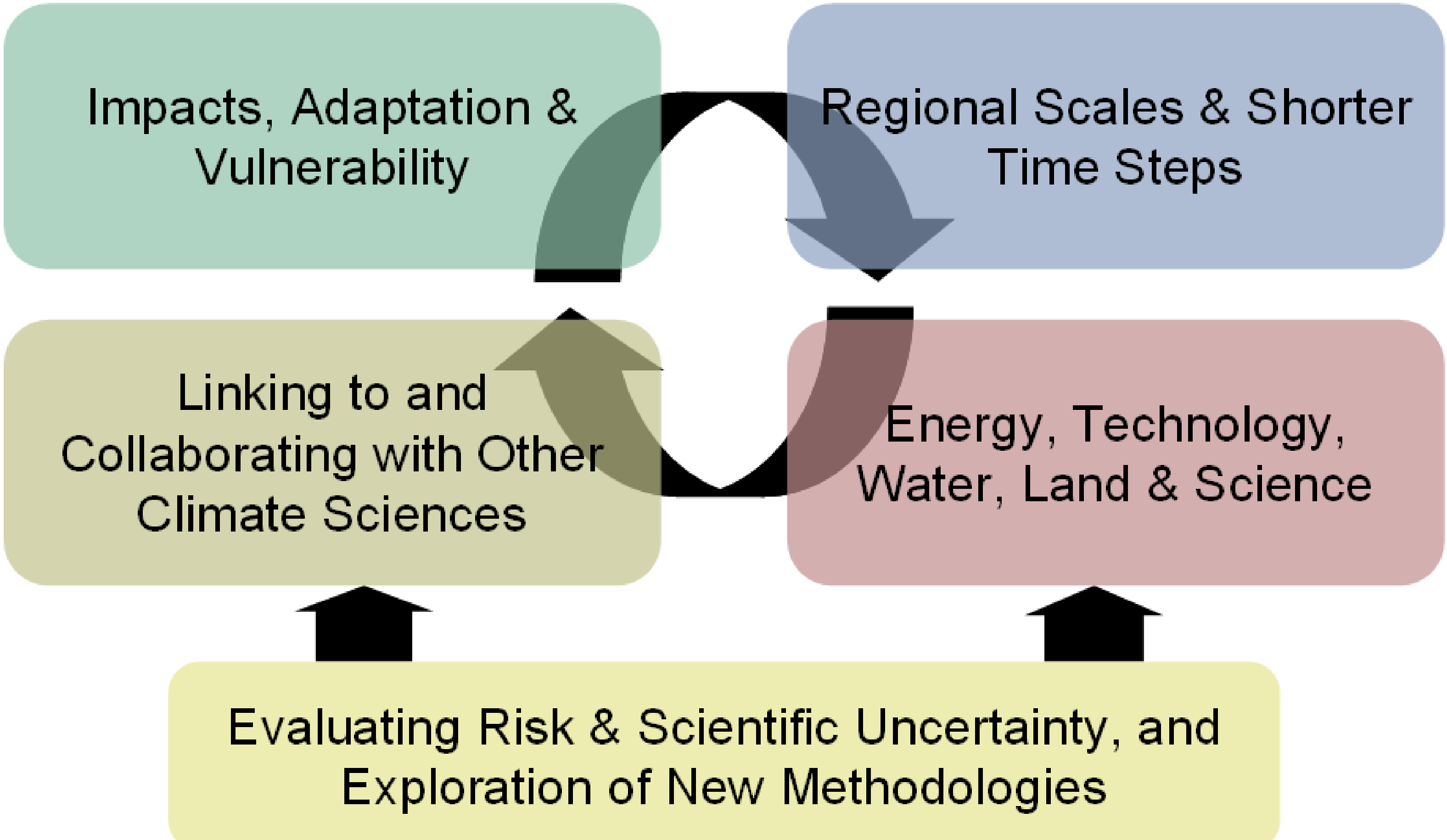
IAM Research Challenges



DISCUSSION

Summary of the DICE model

Stephen C. Newbold
U.S. EPA, National Center for Environmental Economics[1]

This report gives a brief summary of the DICE (Dynamic Integrated Climate-Economy) model, developed by William Nordhaus, which "integrate[s] in an end-to-end fashion the economics, carbon cycle, climate science, and impacts in a highly aggregated model that allow[s] a weighing of the costs and benefits of taking steps to slow greenhouse warming" (Nordhaus and Boyer 2000 p 5). Section 1 of this report recounts the major milestones in the development of DICE and its regionally disaggregated companion model, RICE. This section also serves as a convenient reference for more detailed expositions of the model and applications in the primary literature. Section 2 describes the basic structure of the most recently published version of DICE, and Section 3 describes some key aspects of the model calibration. Section 4 gives additional details on the climate damage function in DICE, and Section 5 gives a brief description of the most recently published version of the RICE model.

1 Historical development

The DICE integrated assessment model has been developed in a series of reports, peer reviewed articles, and books by William Nordhaus and colleagues over the course of more than thirty years. The earliest precursor to DICE was a linear programming model of energy supply and demand with additional constraints imposed to represent limits on the peak concentration of carbon dioxide in the atmosphere (Nordhaus 1977a,b).[2] The model was dynamic, in that it represented the time paths of the supply of energy from various fuels and the demand for energy in different sectors of the economy and the associated emissions and atmospheric concentrations of carbon dioxide. However, it included no representation of the economic impacts or damages from temperature or other climate changes. Later, Nordhaus (1991) developed a long-run steady-state model of the global economy that included estimates of both the costs of abating carbon dioxide emissions and the long term future climate impacts from climate change. This allowed for a balancing of the benefits and costs of carbon dioxide emissions to help determine the optimal level of near term controls. The analysis centered on

[1] Prepared for the EPA/DOE workshop, *Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis*, Washington DC, November 18-19, 2010. Please note that the views expressed in this paper are those of the author and do not necessarily represent those of the U.S. Environmental Protection Agency. No Agency endorsement should be inferred. Author's email: newbold.steve@epa.gov.

[2] While it has not been the focus of the DICE model, it should be emphasized that this type of cost-effectiveness framework is still useful. For example, if policy makers decide upon a 2 degree target, then the appropriate social cost of carbon to use is the shadow price associated with that path (Nordhaus, personal communication).

the global average surface temperature, which was "…chosen because it is a useful index (in the nature of a sufficient statistic) of climate change that tends to be associated with most other important changes rather than because it is the most important factor in determining impacts" (Nordhaus 1991 p 930). The categories of climate damages that were represented in the model were associated with market sectors that accounted for roughly 13% of GDP in the United States. [3]

The DICE model was first presented in its modern form by Nordhaus (1992a,b), who described the new, fully dynamic Ramsey-type optimal growth structure of the model and the optimal time path of emission reductions and associated carbon taxes that emerged from it. The full derivation and extended description of the DICE model and a wider range of applications were presented in a book by Nordhaus (1994a). The next major advance involved disaggregating the model into ten different groups of nations to produce the RICE (Regional DICE) model, which allowed the authors to examine national-level climate policies and different strategies for international cooperation (Nordhaus and Yang 1996). An update and extended description of both RICE (now with eight regions) and DICE appeared in the book by Nordhaus and Boyer (2000). The next major update of DICE, modified to include a backstop technology that can replace all fossil fuels and whose price was projected to decline slowly over time, appeared in another book by Nordhaus (2008). Finally, Nordhaus (2010) described the most recent version of the RICE model, which adds an explicit representation of damages due to sea level rise.

In addition to the studies by Nordhaus and colleagues mentioned above, DICE has been adapted by other researchers to examine a wide range of issues related to the economics of climate change. A comprehensive review is well beyond the scope of this summary, so only a few examples are mentioned here. Pizer (1999) used DICE to compare carbon tax and a cap-and-trade-style policies under uncertainty. Popp (2005) modified DICE to include endogenous technical change. Baker *et al*. (2006) used DICE to examine the effects of technology research and development on global abatement costs. Hoel and Sterner (2007) modified the utility function in DICE to include a form of non-market environmental consumption that is an imperfect substitute for market consumption, and Yang (2008) used RICE in a cooperative game theory framework to examine strategies for international negotiations of greenhouse gas mitigation policies and targets.

2 Basic model structure

DICE2007 is a modified Ramsey-style optimal economic growth model, where an additional form of "unnatural capital"—the atmospheric concentration of CO_2—has a negative

[3] It should be emphasized that while this model and all subsequent versions of DICE necessarily make assumptions about climate and economic conditions in the far future, the important question is the extent to which current policies are robust to changes in assumptions about future variables (Nordhaus, personal communication).

effect on economic output through its influence on the global average surface temperature. Global economic output is represented by a Cobb-Douglas production function using physical capital and labor as inputs. Labor is assumed to be proportional to the total global population, which grows exogenously over time. Total factor productivity also increases exogenously over time. The carbon dioxide intensity of economic production and the cost of reducing carbon dioxide emissions decrease exogenously over time. In each period a fraction of output is lost according to a Hicks-neutral climate change damage function. The output in each period is then divided between consumption, investment in the physical capital stock (savings), and expenditures on emissions reductions (akin to investment in the natural capital stock). DICE solves for the optimal path of savings and emissions reductions over a multi-century planning horizon, where the objective to be maximized is the discounted sum of all future utilities from consumption. Total utility in each period is the product of the number of individuals alive and the utility of a representative individual with average income in that period. The period utility function is of the standard constant relative risk aversion (CRRA) form, and utilities in future periods are discounted at a fixed pure rate of time preference.

3 Calibration

The climate model in DICE2007 tracks the stocks and flows of carbon in three aggregate compartments of the earth system: the lower atmosphere, the shallow ocean, and the deep ocean. The transfer coefficients linking the flows among the compartments were "calibrated to fit the estimates from general circulation models and impulse-response experiments, particularly matching the forcing and temperature profiles in the MAGICC model" (Nordhaus 2008 p 54). The climate sensitivity parameter—the equilibrium change in global average surface temperature after a sustained doubling of atmospheric carbon dioxide concentration—was set to 3 degrees Celsius, which is near the middle of the range cited by the IPCC. The projected temperature change under the baseline scenario (with no climate controls for the first 250 years) is an increase in global average surface temperature of 3.2 degrees Celsius around year 2100 with a peak of around 6.5 degrees Celsius around year 2500.

The key economic growth and preference parameters of DICE2007 are calibrated as follows. The global population is projected to grow exogenously from around 6.5 billion in 2005 to 8.6 billion around 2200. Total factor productivity growth and the discount rate parameters were calibrated to match market returns in the early periods of the model: specifically, "We have chosen a time discount rate of 1½ percent per year along with a consumption elasticity of 2. With this pair of assumptions, the real return on capital averages around 5½ percent per year for the first half century of the projections, and this is our estimate of the rate of return on capital" (Nordhaus 2008 p 61).

The abatement cost function is specified such that the marginal abatement cost, measured as a fraction of output, increases roughly with the square of the fraction of emissions abated. The backstop price—the marginal cost of eliminating the last unit of emissions in each period—is $1,170 per metric ton of carbon in the first period and falls exponentially at a rate of 5% per decade to a long run value of $585 per metric ton of carbon.

The climate damage function is specified such that for small temperature changes the fraction of output lost in each period increases with the square of the increase in temperature above the preindustrial average temperature.[4] The coefficient of the damage function is calibrated so that roughly 1.7% of global economic output is lost when the average global surface temperature is elevated by 2.5 degrees Celsius above the preindustrial average.

4 Damages

The globally aggregated climate damage function in DICE has been calibrated to match the sum of climate damages in all regions represented in the RICE model. The potential damages from climate change are divided into seven categories: agriculture, sea level rise, other market sectors, human health, nonmarket amenity impacts, human settlements and ecosystems, and catastrophes. A full recounting of the derivation of the damage functions in all categories is beyond the scope of this short summary, but to the give the reader a flavor for what is involved this section reviews three categories of damages: agriculture, heath, and catastrophes. This discussion draws heavily on Chapter 4 of Nordhaus and Boyer (2000), so the reader is referred there for more information.

Agriculture can serve as an illustrative example of some of the other categories not covered here. The basic strategy for calibrating the damage functions is to draw on estimates from previous studies of the potential economic losses in each category at a benchmark level of warming of 2.5 degrees Celsius, extrapolating across regions as necessary to cover data gaps in the literature. Some extrapolations were made using income elasticities for each impact category. As the authors explain, "United States agriculture can serve here as an example. Our estimate is that [the fraction of the value of agricultural output lost at 2.5 degrees Celsius] is 0.065 percent [based on Darwin *et al*. 1995]… The income elasticity of the impact index is estimated to be -0.1, based on the declining share of agriculture in output as per capita output rises" (Nordhaus and Boyer 2000 p 74-75).

The human health impacts of climate change were based on the effects of pollution and a broad group of climate-related tropical diseases including malaria and dengue fever. The increased mortality from warming in the summer and decreased mortality from warming in the winter were assumed to roughly offset and so were not included. The specification of the human health damage function involved "a regression of the logarithm of climate related [years

[4] The DICE2007 damage function has an "S-shape," so for very large temperature changes the fraction of output lost increases with temperature at a decreasing rate and asymptotes to one. However, it should be emphasized that the damage function is calibrated to damages in the range of 2 to 4 degrees Celsius. The extent of non-linearity beyond this range is unknown, so extrapolations beyond this point should not be considered reliable (Nordhaus, personal communication).

of life lost] on mean regional temperature estimated form the data presented in Murray and Lopez [1996]" with judgmental adjustments "to approximate the difference among subregions that is climate related," and each year of life lost was valued at two years of per capita income (Nordhaus and Boyer 2000 p 80-82).

The damages from potential catastrophic impacts were estimated using results from a previous survey of climate experts by Nordhaus (1994b). The experts were asked for their best professional judgment of the likelihood of a catastrophe—specified as a 25 percent loss of global income indefinitely—if the global average surface temperature increased by 3 and by 6 degrees Celsius within 100 years. The averages of the survey responses were adjusted upward somewhat based on "[d]evelopments since the survey [that] have heightened concerns about the risks associated with major geophysical changes, particularly those associated with potential changes in thermohaline circulation" (Nordhaus and Boyer 2000 p 87). The probability of a 30 percent loss of global income indefinitely was assumed to be 1.2 and 6.8 percent with 2.5 and 6 degrees Celsius of warming, respectively. The percent of income lost was assumed to vary by region, and a coefficient of relative risk aversion equal to 4 was used to calculate the willingness to pay to avoid these risks in each region. The resulting "range of estimates of WTP lies between 0.45 and 1.9 percent of income for a 2.5^{o}C warming and between 2.5 and 10.8 percent of income for a 6^{o}C warming. It is assumed that this WTP has an income elasticity of 0.1" (Nordhaus and Boyer 2000 p 89).

Damages in the remaining categories were estimated in a similar vein, using a combination of empirical estimates from previous climate impact studies and professional judgments when needed to close the sometimes wide gaps in the literature. The table below shows the resulting global estimates of damages in each category in the 1999 version of RICE.

Damages as a percent of global output at 2.5^{o}C of warming

	Output weighted	Population weighted
Agriculture	0.13	0.17
Sea level rise	0.32	0.12
Other market sectors	0.05	0.23
Health	0.10	0.56
Non-market amenities	-0.29	-0.03
Human settlements and ecosystems	0.17	0.10
Catastrophes	1.02	1.05
Total	1.50	1.88

(Nordhaus and Boyer 2000 p 91)

With damages in all categories estimated, the DICE damage function was then calibrated "so that the optimal carbon tax and emissions control rates in DICE-99 matched the projections of these variables in the optimal run of RICE-99" (Nordhaus and Boyer 2000 p 104).

5 Recent developments

Nordhaus (2010) presented results from an updated version of the RICE model. A major extension is a new sea level rise damage function, now explicitly modeled by region as a function of the global average sea level rise rather than rolled up in the aggregate damage function. "The RICE-2010 model provides a revised set of damage estimates based on a recent review of the literature [Toll 2009, IPCC 2007]. Damages are a function of temperature, SLR, and CO_2 concentrations and are region-specific. To give an idea of the estimated damages in the uncontrolled (baseline) case, those damages in 2095 are… 2.8% of global output, for a global temperature increase of 3.4^{o}C above 1900 levels" (Nordhaus 2010 p 3). Other parameter updates include climate sensitivity, now set to 3.2 degrees Celsius, the elasticity of the marginal utility of income, now set to -1.5, and parameters that control economic growth rates, which are re-calibrated such that world per capita consumption grows by an average rate of 2.2% per year for the first 50 years.

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Summary of the DICE model

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The views expressed in this presentation are those of the author and do not necessarily represent those of the U.S. Environmental Protection Agency. No Agency endorsement should be inferred.

Outline

1. Historical development
2. Applications
3. One-slide summary
4. Model structure
5. The SCC in DICE
6. Calibration of global damage function
7. Quick update: RICE2010

Historical development

- Nordhaus WD. 1977. Strategies for the control of carbon dioxide. Cowles Foundation Discussion Paper.
- Nordhaus WD. 1977. Economic growth and climate: the carbon dioxide problem. *AER* 67(1):341-346.
- Nordhaus WD. 1991. To slow or not to slow: the economics of the greenhouse effect. *The Economics Journal* 101(407):920-937.
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- Nordhaus WD. 2008. *A Question of Balance.* Cambridge, MA: MIT Press.
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Applications

DICE is designed to:

- "…estimate the optimal path of capital accumulation and GHG – emissions reductions" (Nordhaus 1992, 1994).

- Compare taxes versus quantity controls under uncertainty, and investigate value of early information (Nordhaus 1994 Ch 8).

- Compare business as usual scenario and optimized policy to alternatives, e.g., Kyoto Protocol, similar to Stern Review, Gore emission reductions, temperature constraints (Nordhaus 2008).

- "Examine alternative outcomes for emissions, climate change, and damages under different policy scenarios" and calculate the near term carbon prices along alternative policy paths (Nordhaus 2010).

Applications

DICE has been modified by others to examine a wide range of climate change economics issues, e.g.,

- Pizer (1999) [P vs Q for climate policy]
- Popp (2004) [endogenous technical change]
- Baker *et al*. (2006) [optimal R&D policy]
- Hoel and Sterner (2007) [relative prices of market vs non-market consumption]
- Yang (2008) [strategic bargaining in international negotiations]
- de Bruin *et al*. (2009) [optimal adaptation policy]

One-slide summary

- **D**ynamic **I**ntegrated **C**limate**-E**conomy model
- Optimal economic growth model **+** a simplified climate change model **+** a damage function that represents the loss of economic output due to increased global surface temperatures **+** projection of abatement costs over time.
- Solves for optimal path of savings and abatement to maximize present value of discounted aggregate utility.
- Some key results from DICE2007 (Nordhaus 2008):
  - SCC_{2005} in baseline scenario ≈ \$7.5/tCO_2 (≈ optimal carbon tax)
  - SCC growth rate ≈ 0.02/yr
  - Max temp increase ≈ 6°C (no controls for 250 yrs); ≈ 3.5°C (optimal)
- New results from RICE2010 in Nordhaus (2010) *PNAS*

Model structure

- Net output = gross output from economic production
  – fraction of output lost due to climate damages
  – fraction of output spent on abatement
- Consumption = net output – savings
- Capital accumulation = savings – depreciation
- Temperature = "three-box" climate model calibrated to MAGGIC
- Choose savings and abatement to max present value of future utilities, where utility depends on per-capita consumption in each period
- Key quantities:
  - Pure rate of time preference = 0.015/yr
  - Elasticity of m.u. of consumption = -2
  - Initial per capita consumption growth rate ≈ 0.016/yr
  - Damages at 3 deg C ≈ 2.5% of world GDP
  - Damages at 6 deg C ≈ 9.3% of world GDP

The SCC in DICE

Social cost of carbon = shadow value of emissions ÷
shadow value of capital stock

Along an optimal path this will equal:

1. the change in consumption in all future years from one additional unit of emissions in the current year, discounted to present value using the Ramsey consumption discount rate, and

2. the tax on CO_2 emissions.

Calibration of damage function

Basic strategy:

1. Choose a functional form for aggregate climate change damages as a fraction of global economic output (e.g., low order polynomial).

2. Calibrate damage function parameters using summary of empirical studies of climate change damages in all major categories, extrapolating among regions as necessary:

   agriculture, sea-level rise, other market sectors, health, nonmarket amenity impacts, human settlements and ecosystems, catastrophes.

(Nordhaus & Boyer 2000)

Sector by sector

Example 1 – Agriculture:

- Similar calibration strategy for some other sectors
- Draw on estimates from previous studies of the potential economic losses in each category at a benchmark level of warming of 2.5^{o}C
- Extrapolate across regions as necessary to cover data gaps using income elasticities for each impact category
- "United States agriculture can serve here as an example. Our estimate is that [the fraction of the value of agricultural output lost at 2.5^{o}C] is 0.065 percent [based on Darwin *et al*. 1995]… The income elasticity of the impact index is estimated to be -0.1, based on the declining share of agriculture in output as per capita output rises" (Nordhaus and Boyer 2000 p 74-75).

Sector by sector

Example 2 – Health:

- Based on effects of pollution and a broad group of climate-related tropical diseases including malaria and dengue fever
- Changes in mortality from more severe summers and less severe winters were assumed to roughly offset and so were not included
- Using data from Murray and Lopez (1996), regress the log of climate related YLLs [years of life lost] on mean regional temperature
- Plus judgmental adjustments “to approximate the difference among subregions that is climate related”
- Each YLL valued at two years of per capita income (Nordhaus and Boyer 2000 p 80-82).

Sector by sector

Example 3 – Catastrophes:

- Based on results from survey of climate experts (Nordhaus 1994). Experts asked for likelihood of a catastrophe (i.e., 25% loss of global income indefinitely) if the global average temp increased by 3^{o}C and by 6^{o}C within 100 years.
- Average responses adjusted upward based on "heightened concerns about the risks associated with major geophysical changes…"
- Probability of 30% loss of global income assumed to be 1.2% with 2.5^{o}C and 6.8% with 6^{o}C of warming. CRRA = 4 used to calculate WTP to avoid catastrophic risks.
- WTPs between 0.45% and 1.9% of income for 2.5^{o}C and between 2.5% and 10.8% for 6^{o}C warming. Assumed that this WTP has income elasticity = 0.1

Sector by sector

Category	Damages at 2.5°C [% of global output]	
	Output weighted	Population weighted
Agriculture	0.13	0.17
Sea-level rise	0.32	0.12
Other market sectors	0.05	0.23
Health	0.10	0.56
Non-market amenities	-0.29	-0.03
Human settlements & ecosystems	0.17	0.10
Catastrophes	1.02	1.05
Total	**1.50**	**1.88**

(Nordhaus & Boyer 2000)

Aggregation of damages

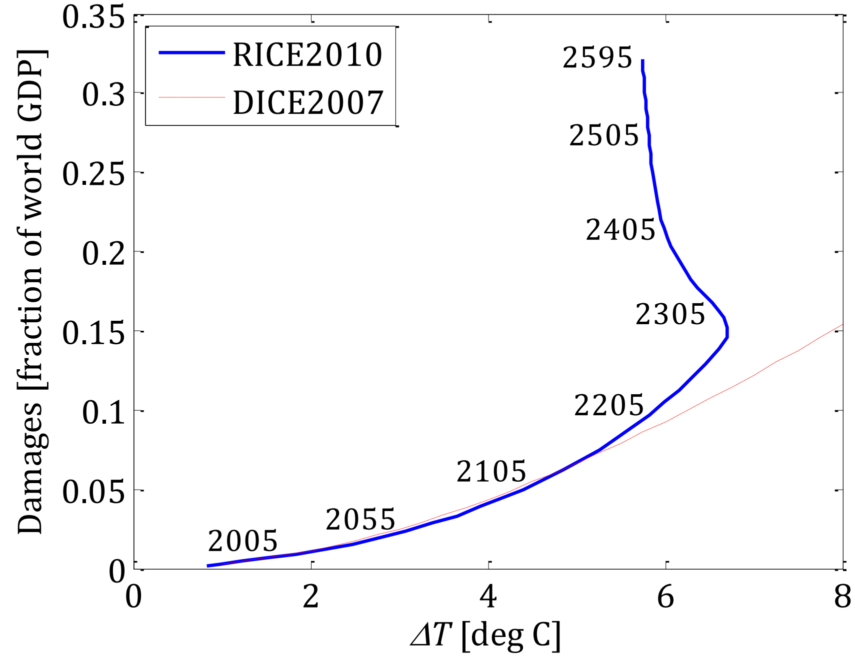
RICE/DICE1999 (Nordhaus & Boyer 2000):

1. Calculate regional impacts for 2.5^{o}C and 6^{o}C.
2. Sum across categories to create overall impacts for each region.
3. Solve system of 2 quadratic equations for reach region to obtain quadratic damage function parameters for each region.
4. DICE quadratic damage function calibrated “so that the optimal carbon tax and emissions control rates in DICE-99 matched the projections of these variables in the optimal run of RICE-99.”

Update: RICE2010

Nordhaus (2010):

- Parameters: pure rate of time preference = 0.015/yr, elasticity of m.u. of consumption = -1.5, initial growth rate of per cap consumption ≈ 0.022/yr.
- "…provides a revised set of damage estimates based on a recent review of the literature [Tol 2009, IPCC 2007]. Damages are a function of temperature, SLR, and CO_2 concentrations and are region-specific."
- Near term carbon price on optimal path ≈ $11/ton CO_2



RICE2010 damages plotted against temperature change relative to pre-industrial in each year.

The PAGE09 model: Estimating climate impacts and the social cost of CO2

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October 2010

Introduction

PAGE09 is a new version of the PAGE integrated assessment model that values the impacts of climate change and the costs of policies to abate and adapt to it. The model helps policy makers explore the costs and benefits of action and inaction, and can easily be used to calculate the social cost of CO2 (SCCO2) both today and in the future.

PAGE09 is an updated version of the PAGE2002 integrated assessment model. PAGE2002 was used to value the impacts and calculate the social cost of CO2 in the Stern review (Stern, 2007), the Asian Development Bank's review of climate change in Southeast Asia (ADB, 2009), and the EPA's Regulatory impact Analysis (EPA, 2010), and to value the impacts and costs in the Eliasch review of deforestation (Eliasch, 2008). The PAGE2002 model is described fully in Hope, 2006, Hope, 2008a and Hope, 2008b.

The update to PAGE09 been made to take account of the latest scientific and economic information, primarily in the 4th Assessment Report of the IPCC (IPCC, 2007). This short paper outlines the updated treatment of the science and impacts in the latest default version of the model, PAGE09 v1.7.

PAGE09 uses simple equations to simulate the results from more complex specialised scientific and economic models. It does this while accounting for the profound uncertainty that exists around climate change. Calculations are made for eight world regions, ten time periods to the year 2200, for four impact sectors (sea level, economic, non-economic and discontinuities) which cover all impacts, with the exception of socially contingent impacts such as massive forced migration and the threat of war, for which there are currently no economic estimates.

The treatment of uncertainty is at the heart of the model. In the calculation of the SCCO2, 45 inputs are specified as independent probability distributions; these typically take a triangular form, defined by a minimum, mode (most likely) and maximum value. The model is usually run 10000 times to build up full probability distributions of the scientific and economic results, such as the global mean temperature, the net present value of impacts and the SC CO2.

The full set of model equations and default inputs to the model are contained in a technical report available from the author. Initial results from the model are presented in a companion paper, 'The Social Cost of CO2 from the PAGE09 model'.

The changes made to PAGE2002 to create PAGE09 are outlined below under the following headings: Science, Impacts and Adaptation.

Science

Inclusion of Nitrous Oxide

The number of gases whose emissions, concentrations and forcing are explicitly modelled is increased from 3 in PAGE2002 to 4 in PAGE09. The forcing from N2O takes the same form as for CH4, based on the square root of the concentration. The excess forcing from gases not explicitly modelled is now allowed to vary by policy.

Inclusion of transient climate response

In PAGE2002, the climate sensitivity is input directly as an uncertain parameter. The climate sensitivity in PAGE09 is derived from two inputs, the transient climate response (TCR), defined as the temperature rise after 70 years, corresponding to the doubling-time of CO2 concentration, with CO2 concentration rising at 1% per year, and the feedback response time (FRT) of the Earth to a change in radiative forcing (Andrews and Allen, 2008). Default triangular distributions for TCR and FRT in PAGE09 give a climate sensitivity distribution with a mean of 3 degC, and a long right tail, consistent with the latest estimates from IPCC, 2007.

Feedback from temperature to the carbon cycle

The standard PAGE2002 model contains an estimate of the extra natural emissions of CO2 that will occur as the temperature rises (an approximation for a decrease in absorption in the ocean and possibly a loss of soil carbon (Hope, 2006)). Recent model comparison exercises have shown that the form of the feedback in PAGE2002 works well for business as usual emissions, but overestimates concentrations in low emission scenarios (van Vuuren et al, 2009).

In PAGE09, the carbon cycle feedback (CCF) is introduced as a linear feedback from global mean temperature to a percentage gain in the excess concentration of CO2, to simulate the decrease in CO2 absorption on land and in the ocean as temperature rises (Friedlingstein et al, 2006). PAGE09 is much better than PAGE2002 at simulating the carbon cycle feedback results for low emission scenarios in Friedlingstein et al, 2006, van Vuuren et al, 2009.

Land temperature patterns by latitude

In PAGE2002, regional temperatures vary from the global mean temperature only because of regional sulphate forcing. However, geographical patterns of projected warming show greatest temperature increases over land (IPCC, 2007, ch10, p749), and a variation with latitude, with regions near the poles warming more than those near the equator (IPCC, 2007, ch10, figure 10.8 and supplementary material).

In PAGE09 the regional temperature is adjusted by a factor related to the effective latitude of the region, and one related to the land-based nature of the regions. The adjustment is calculated for each region using an uncertain parameter of the order of 1 degC representing the temperature increase difference between equator and pole, and the effective absolute latitude of the region, and an uncertain constant of the order of 1.4 representing the ratio between mean land and ocean temperature increases.

Explicit incorporation of sea level rise

In PAGE2002, sea level rise is only included implicitly, assumed to be linearly related to global mean temperature. This neglects the different time constant of the sea level response, which is longer than the surface air temperature response (IPPC, 2007, p823).

In PAGE09, sea level is modelled explicitly as a lagged linear function of global mean temperature (Grinsted et al, 2009). The IPCC has a sea level rise projection in 2100 of 0.4 – 0.7 m from pre-industrial times (IPCC , 2007, p409). A characteristic response time of between 500 and 1500 years in PAGE09 gives sea level rises compatible with these IPCC results.

Impacts

Impacts as a proportion of GDP

In PAGE2002, economic and non-economic impacts before adaptation are a polynomial function of the difference between the regional temperature and the tolerable temperature level, with regional weights representing the difference between more and less vulnerable regions. These impacts are then equity weighted, discounted at the consumption rate of interest and summed over the period from now until 2200. There are several issues with this representation, including the lack of an explicit link from GDP per capita to the regional weights, and the possibility that impacts could exceed 100% of GDP with unfavourable parameter combinations.

In PAGE09, extra flexibility is introduced by allowing the possibility of initial benefits from small increases in regional temperature (Tol, 2002), by linking impacts explicitly to GDP per capita and by letting the impacts drop below their polynomial on a logistic path once they exceed a certain proportion of remaining GDP to reflect a saturation in the vulnerability of economic and non-economic activities to climate change, and ensure they do not exceed 100% of GDP.

Figure 1

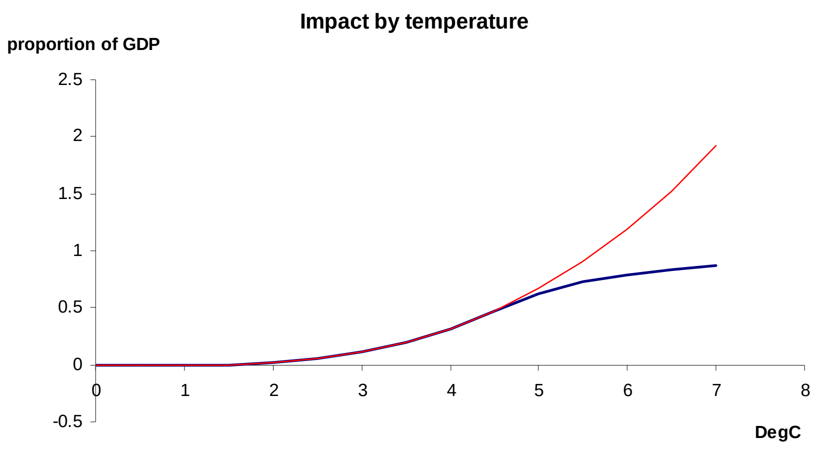


Figure 1 shows such an impact function, with initial benefits (IBEN) of 1% of GDP per degree, with impacts (W) of 4% of GDP at a calibration temperature (TCAL) of 2.5 degC, with a polynomial power (POW) of 3, and an exponent with income (IPOW) of -0.5. The impact function has a saturation(ISAT) starting at 50% of GDP, which keeps the impacts (blue line) below 100% of GDP even for the high temperatures shown. The red line shows what the impacts would be if they continued to follow the polynomial form without saturation.

Discontinuity impacts

As in PAGE2002, the risk of a large-scale discontinuity, such as the Greenland ice sheet melting, is explicitly modelled. In PAGE09 the losses associated with a discontinuity do not all occur immediately, but instead develop with a characteristic lifetime after the discontinuity is triggered (Lenton et al, 2008).

Equity weighting of impacts

In PAGE2002, impacts are equity weighted in a rather ad-hoc way, with the change in consumption increased in poor regions and decreased in rich ones.

PAGE09 uses the equity weighting scheme proposed by Anthoff et al (2009) which converts changes in consumption to utility, and amounts to multiplying the changes in consumption by

$$EQ(r,t) = (G(fr,0)/G(r,t))^{EMUC}$$

where G(r,t) is the GDP per capita in a region and year, G(fr,0) is today's GDP per capita in some focus region (which could be the world as a whole, but in PAGE09 is normally the EU), and EMUC is the negative of the elasticity of the marginal utility of consumption. This equity weighted damage is then discounted at the utility rate of interest, which is the PTP rate.

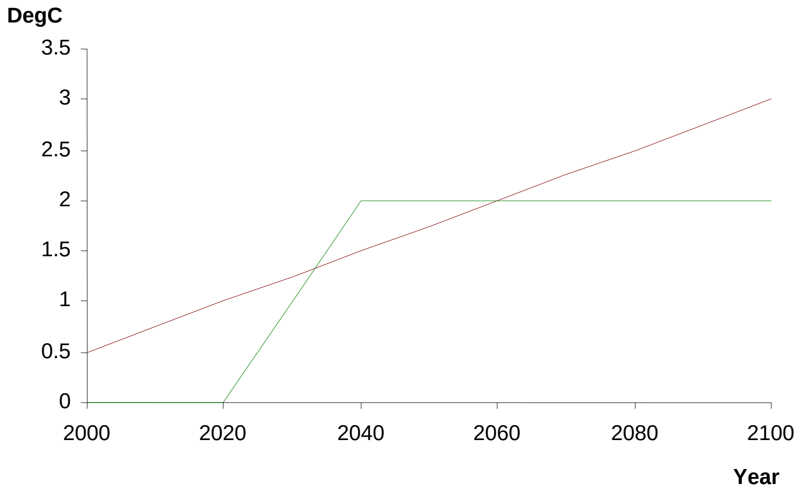
Adaptation

The speed and amount of adaptation is modelled as a policy decision in PAGE. This allows the costs and benefits of different adaptation decisions to be investigated. In PAGE2002, adaptation can increase the natural tolerable level of temperature change, and can also reduce any climate change impacts that still occur.

In PAGE09, there is assumed to be no natural tolerable temperature change, and adaptation policy is specified by seven inputs for each impact sector. The tolerable temperature is represented by the plateau, the start date of the adaptation policy and the number of years it takes to have full effect. The reduction in impacts is represented by the eventual percentage reduction, the start date, the number of years it takes to have full effect and the maximum sea level or temperature rise for which adaptation can be bought; beyond this, impact adaptation is ineffective. Both types of adaptation policy are assumed to take effect linearly with time. An adaptation policy in PAGE09 is thus defined by 7 inputs for 3 sectors for 8 regions, giving 168 inputs in all. This is a simplification compared to the 480 inputs in PAGE2002.

The green line in figure 2 shows an illustrative tolerable temperature profile over time in an impact sector that results from an adaptation policy that gives a tolerable temperature of 2 degC, starting in 2020 and taking 20 years to implement fully. If the temperature rise is shown by the red line, there will be 0.5 degC of impacts in 2000, increasing to 1 deg C by 2020, then reducing to 0 from 2030 to 2060. After 2060 the impacts start again, reaching 1 deg C by 2100.

Figure 2 Temperature and tolerable temperature by date (illustrative)



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Climate impacts in the PAGE09 model

Prepared for the
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Plan of talk

- The PAGE09 model.
- Impacts and the social cost of CO2.
- Comparison with results from PAGE2002

The PAGE09 model

- A development of the PAGE2002 model
- Excel 2007 worksheet with @RISK 5.5 add-in
- 4 greenhouse gases
- 8 regions
- 10 analysis years
- 3 impact sectors and discontinuities
- 2 policies and their difference
- 10000 runs to calculate probability distributions of outputs

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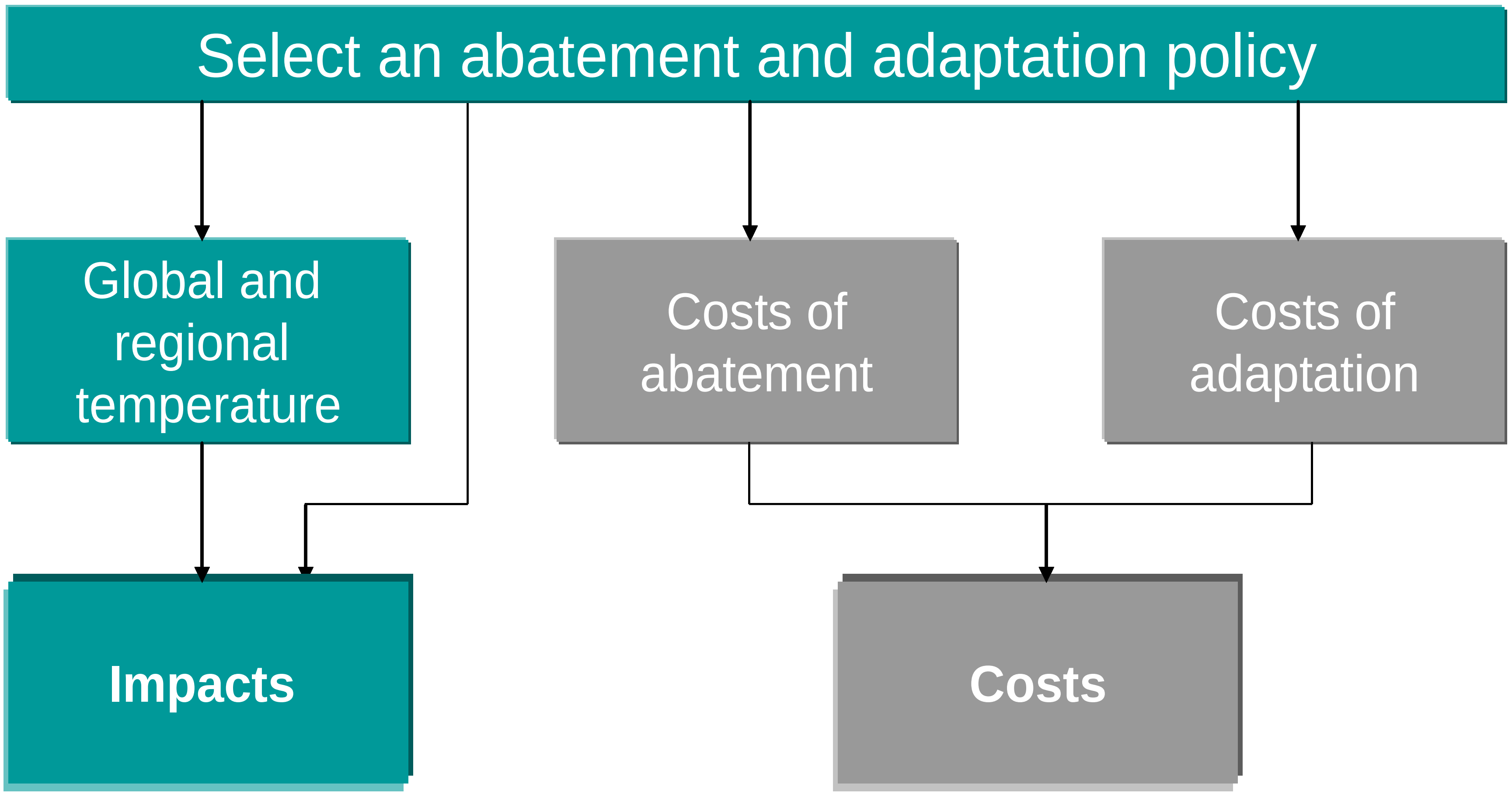
Structure of the PAGE09 model



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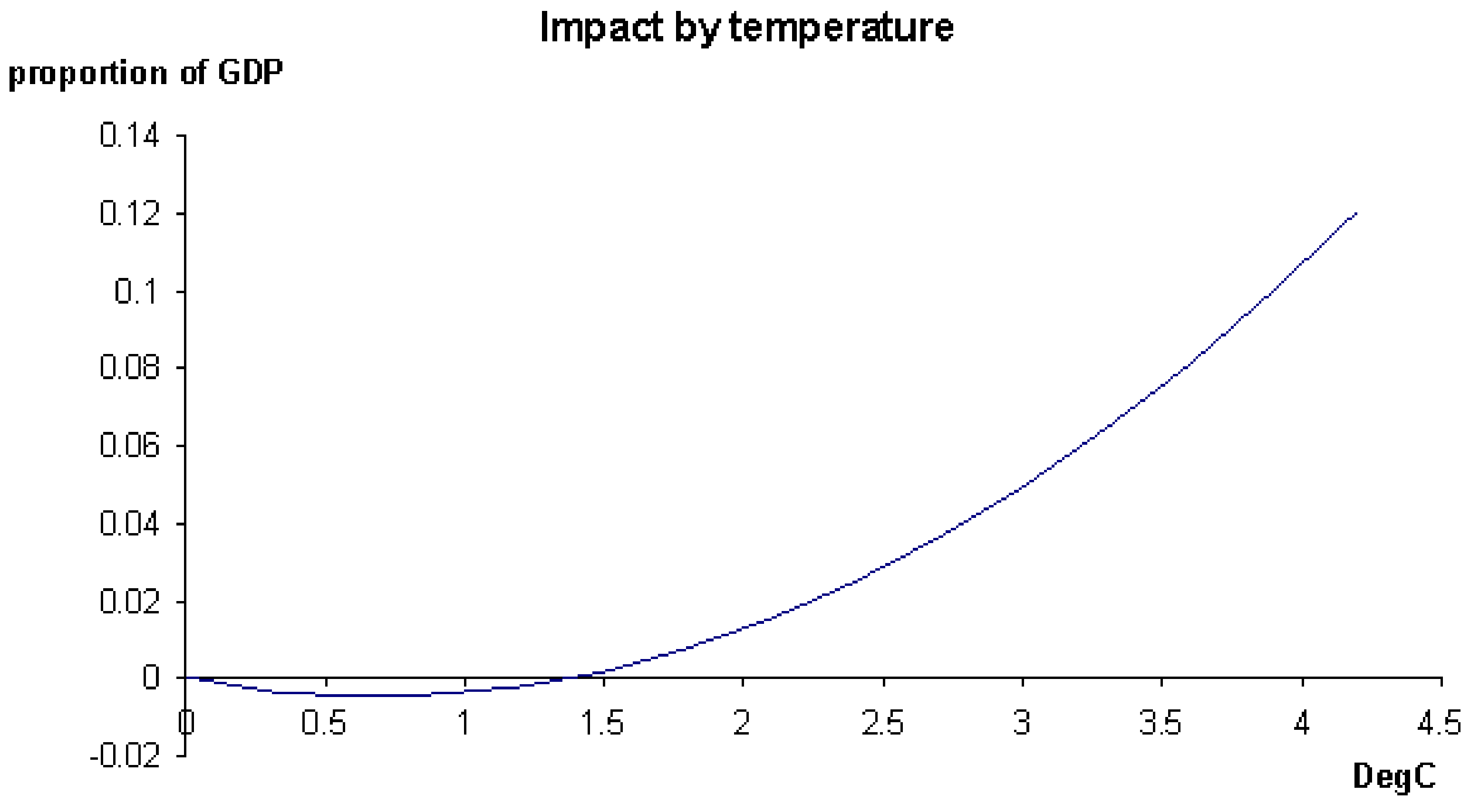
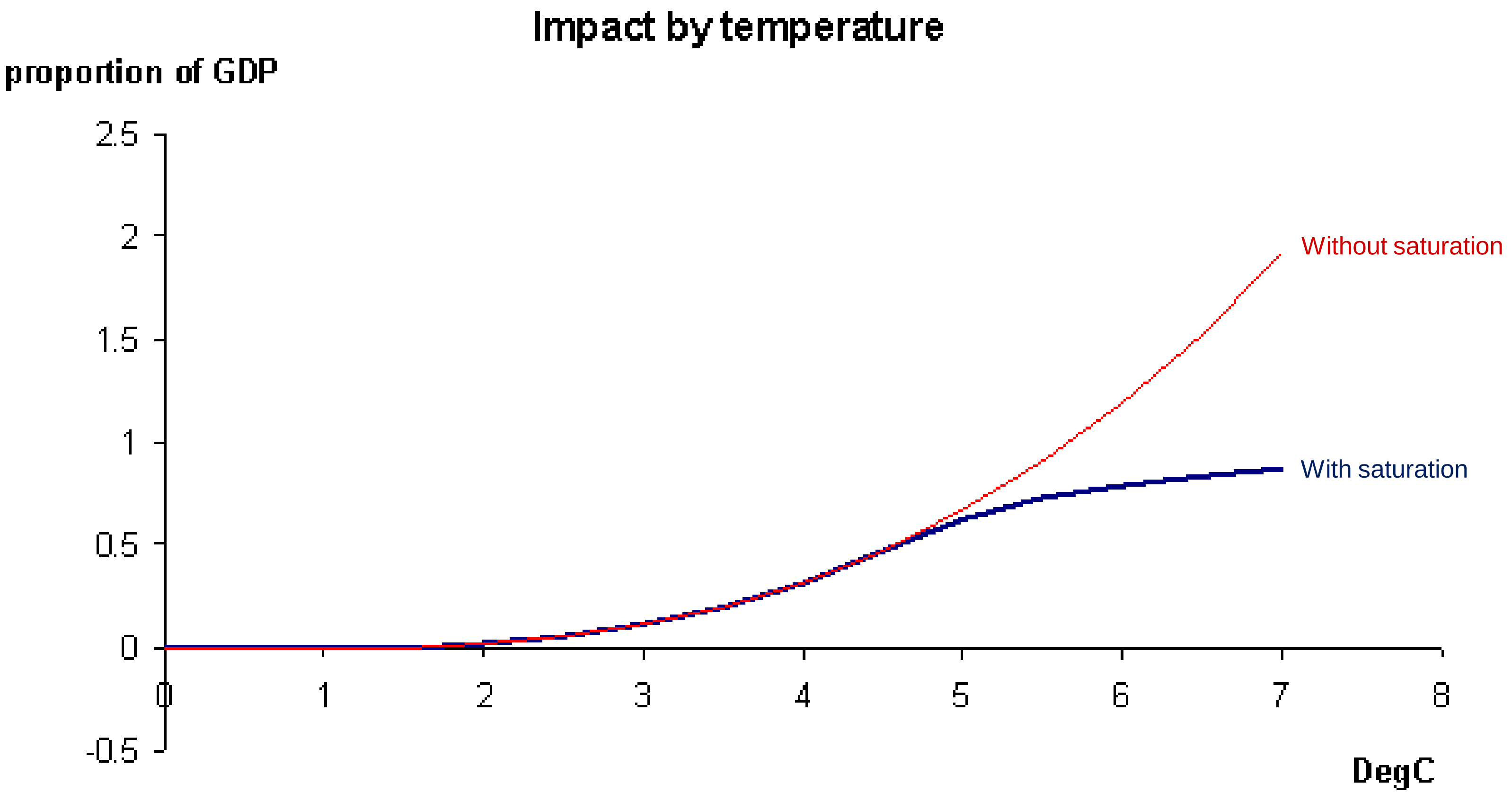
New features of PAGE09

Possibility of benefits



Saturation of impacts



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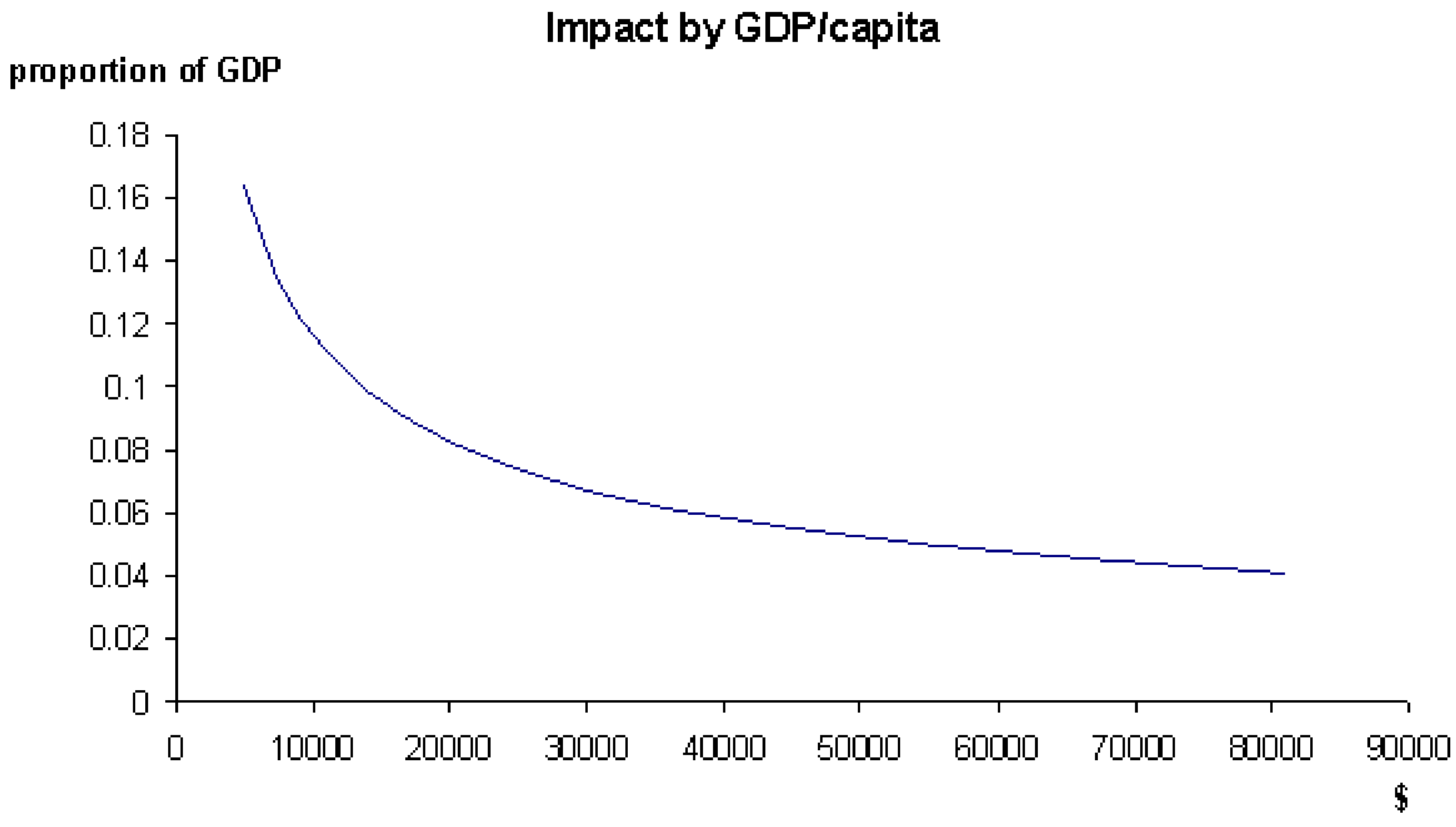
Impacts as a function of GDP/capita



Impacts and $SCCO_2$

- Business as usual scenario: A1B.
- Low emissions scenario: 2016 r5 low.
- Moderate adaptation.
- Currency unit: $2005, PPP exchange rates, EU base year GDP/cap.
- Pure time preference rate: <0.1,1,2> % per year.
- EMUC: <0.5,1,2>.

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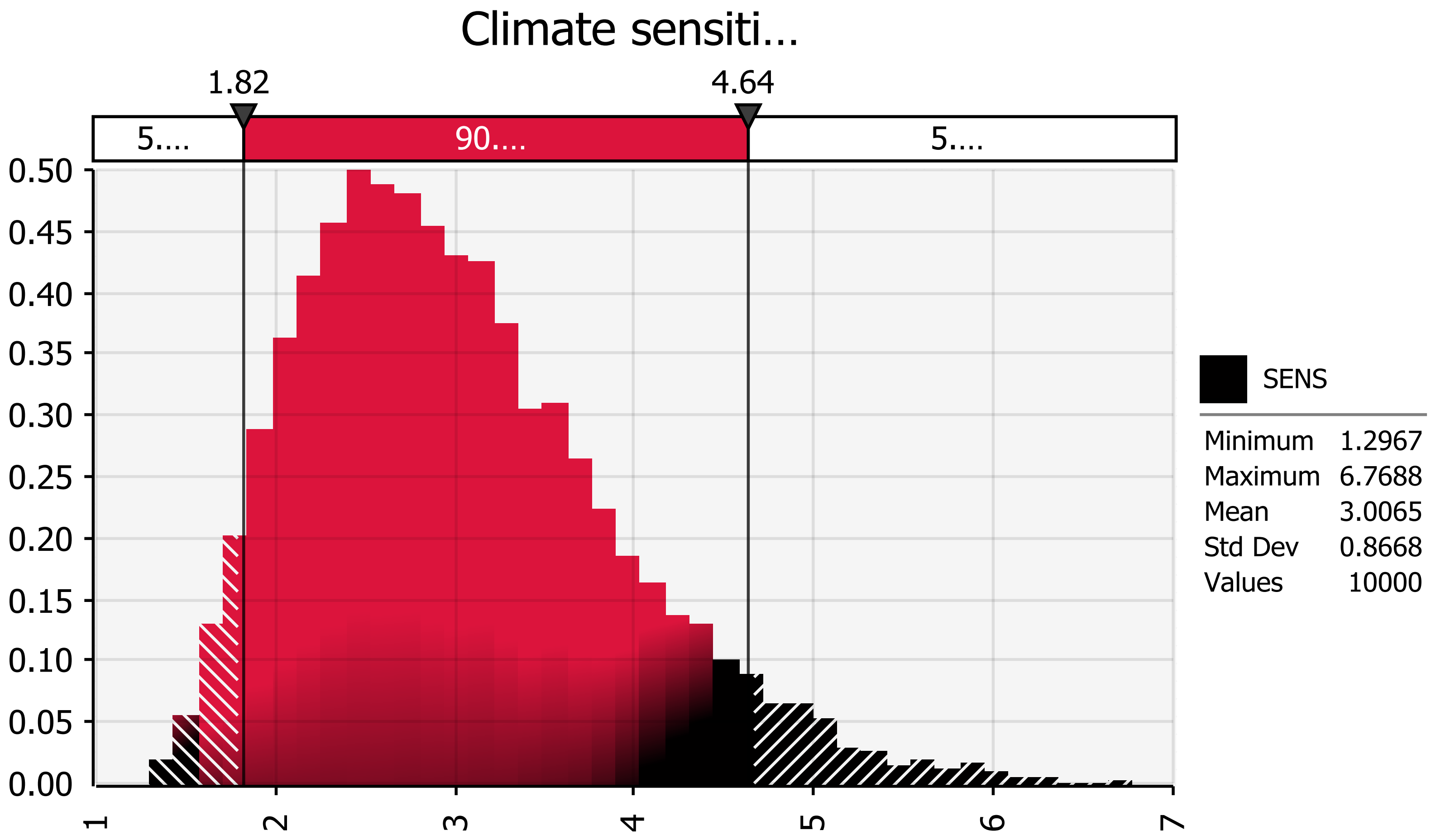

Source: 10000 PAGE09 runs

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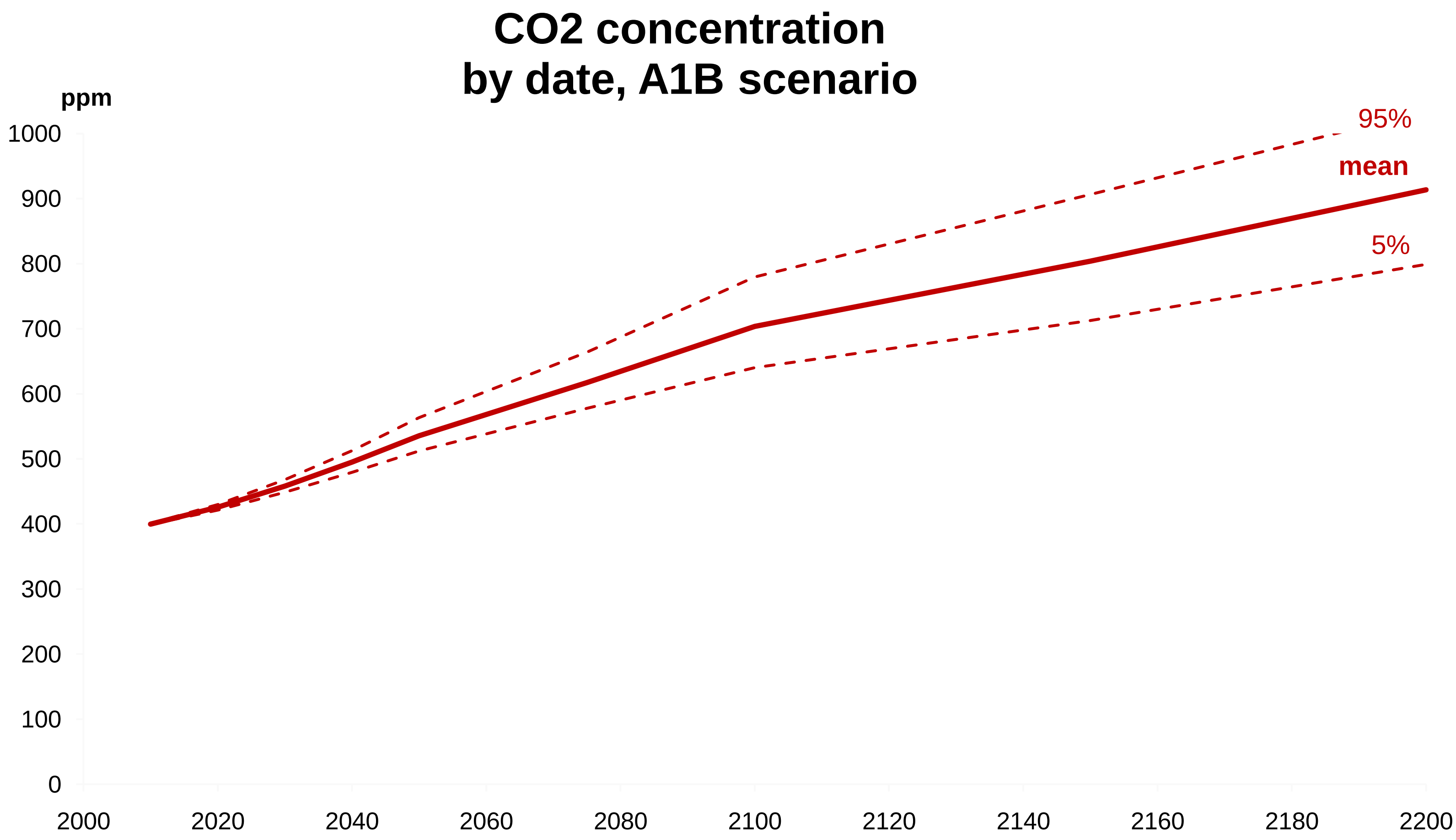

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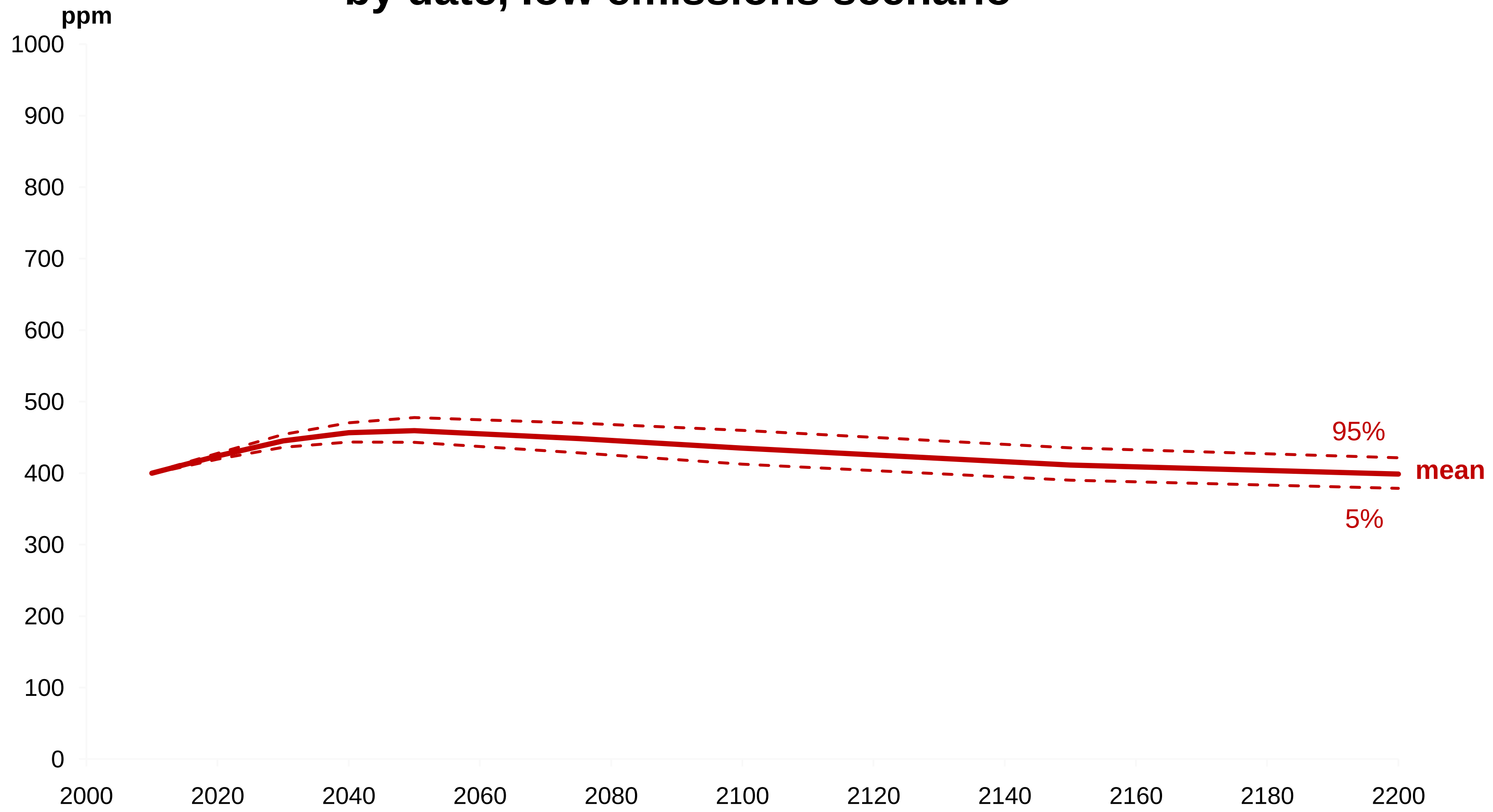
CO2 concentration
by date, low emissions scenario



Source: 10000 PAGE09 runs

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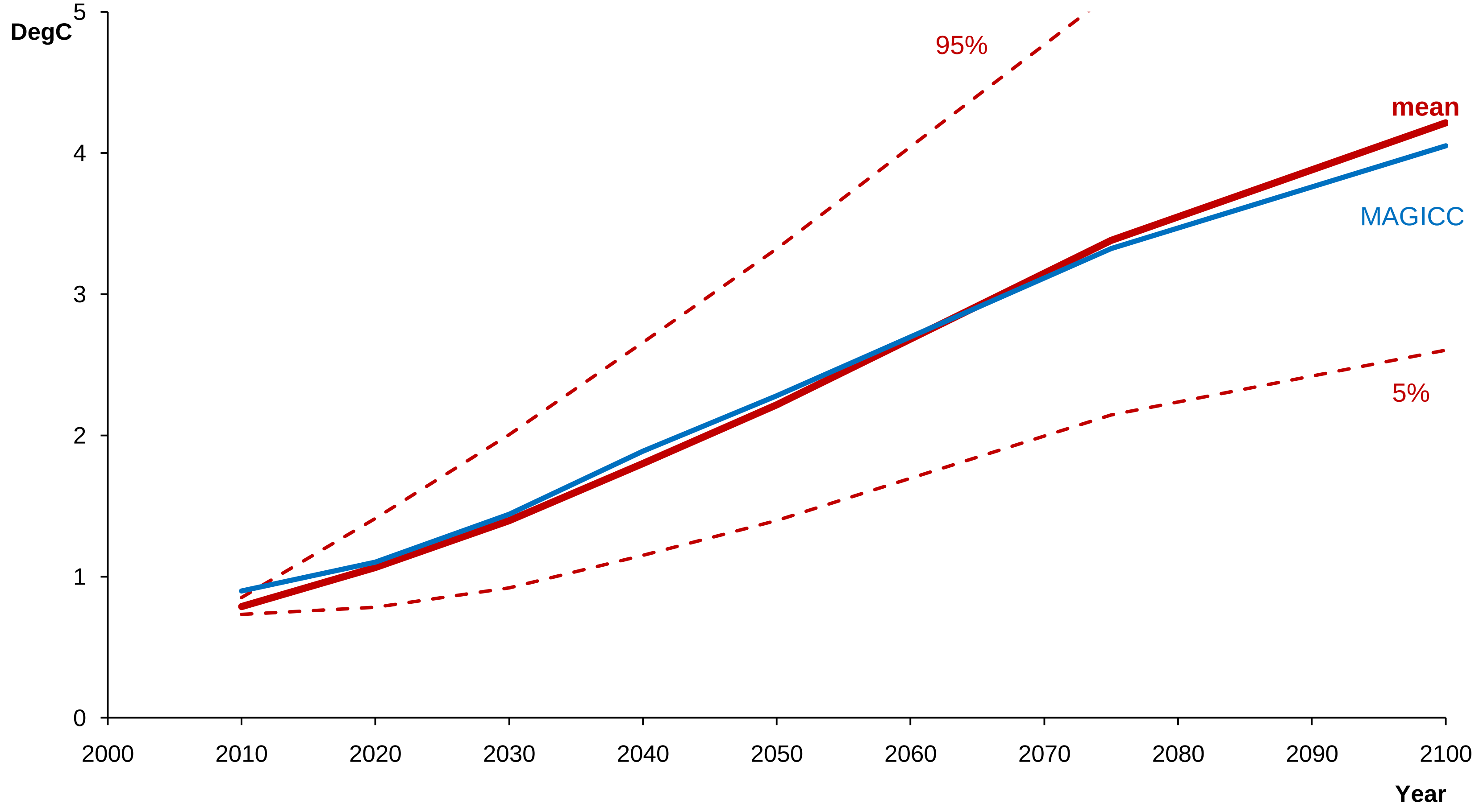
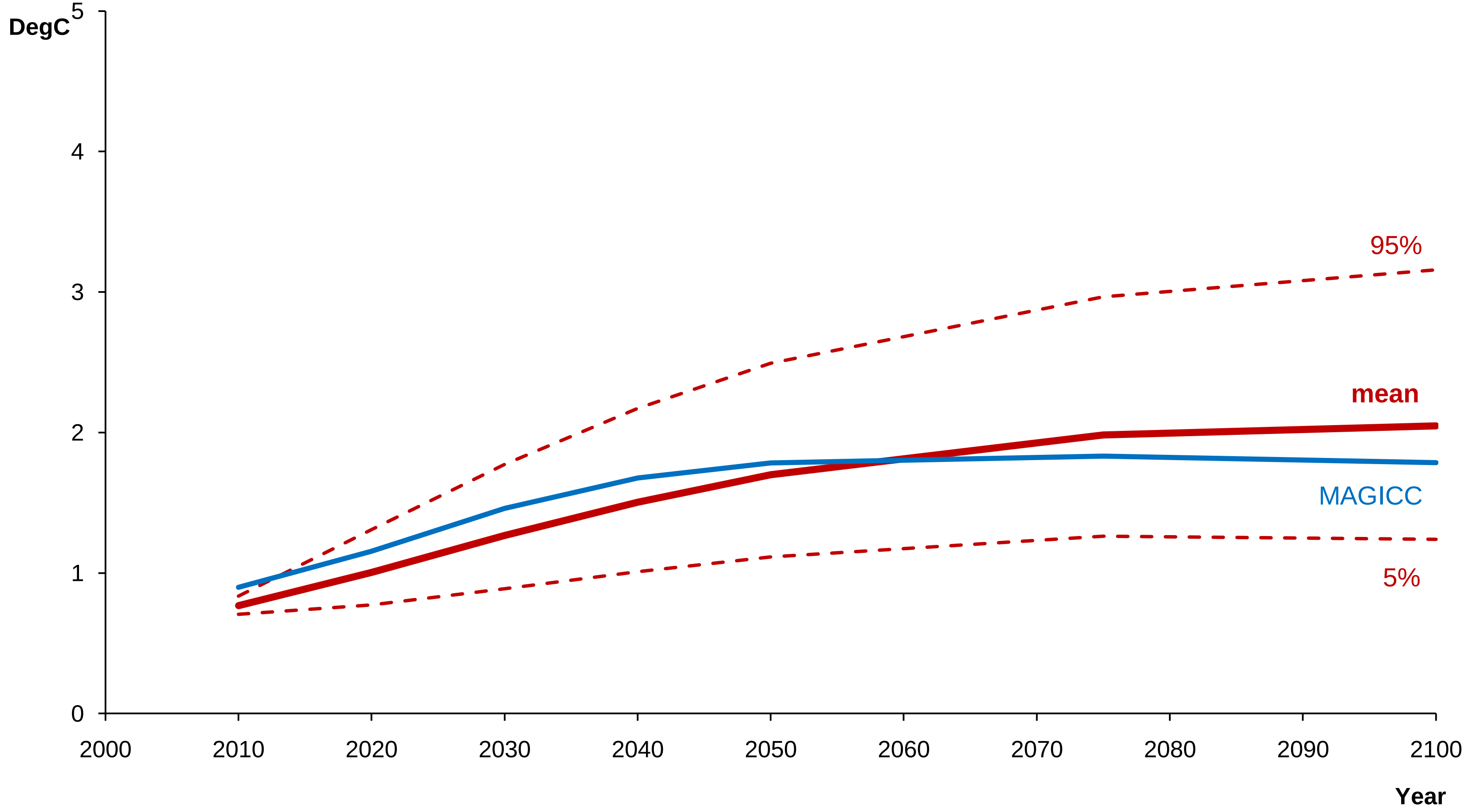
Global mean temperature rise by date, A1B scenario



Source: 10000 PAGE09 runs

Global mean temperature rise by date, low emissions scenario



Source: 10000 PAGE09 runs

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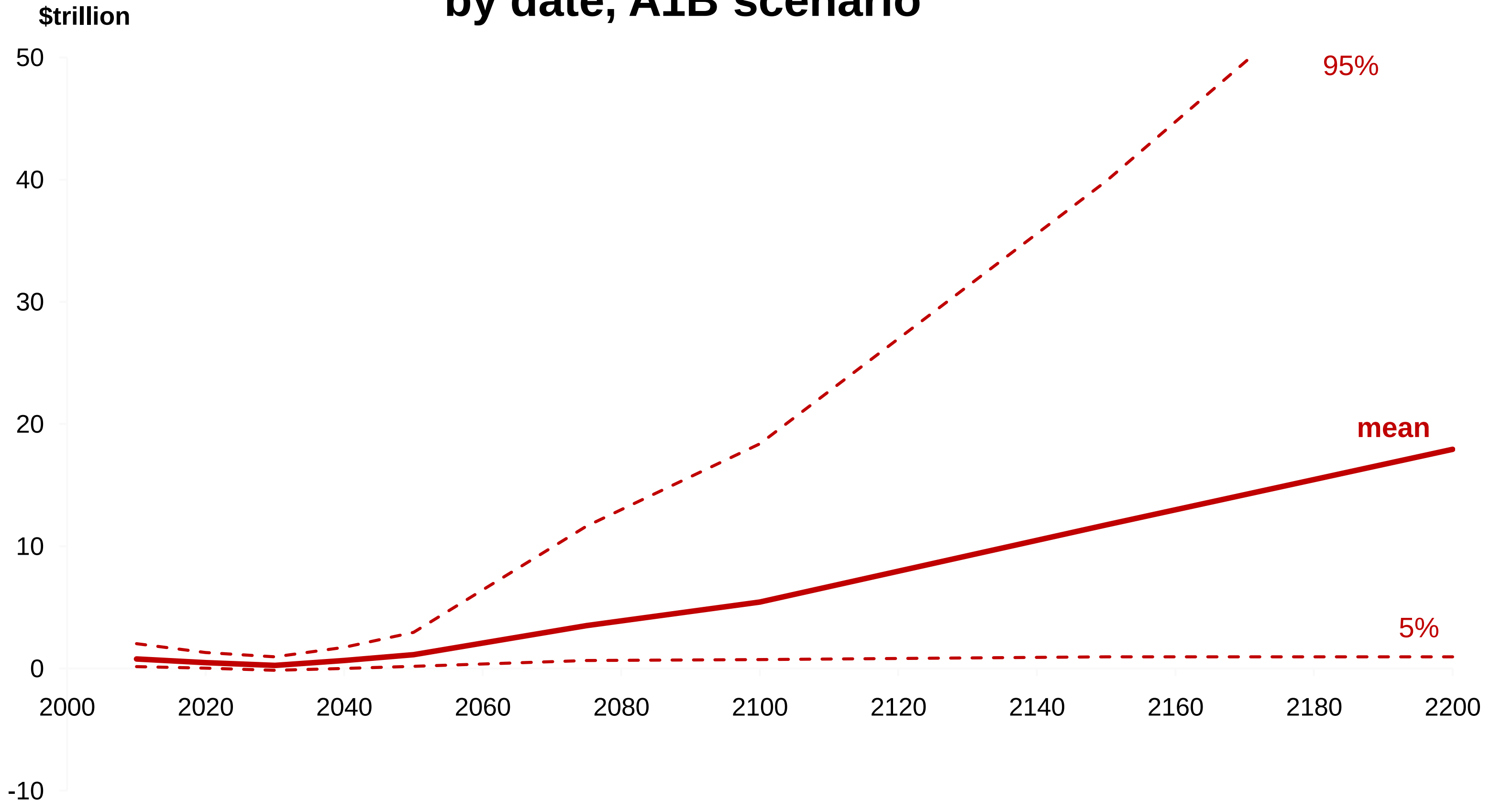
Global impacts by date, A1B scenario



Source: 10000 PAGE09 runs

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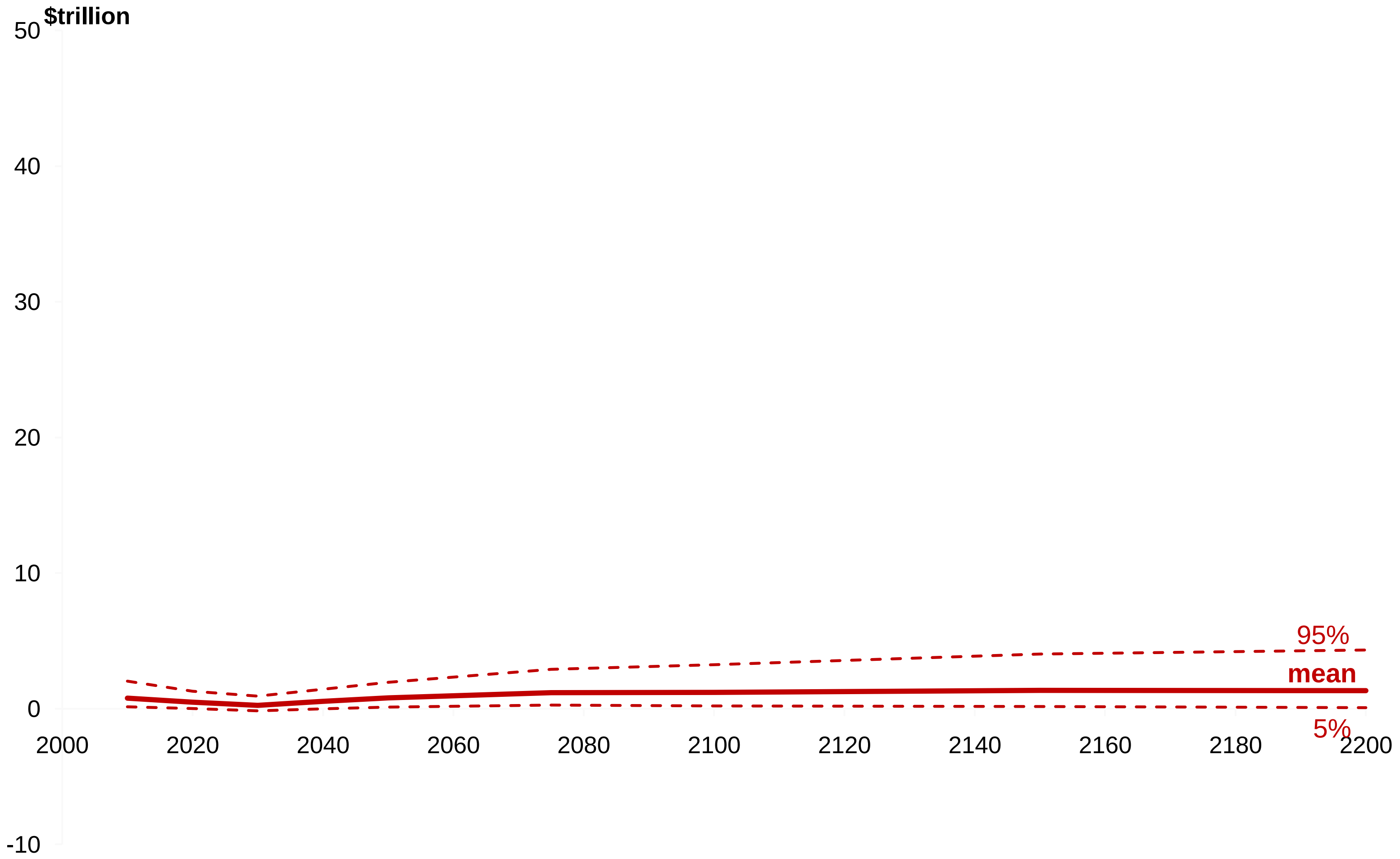
Global impacts by date, low emissions scenario



Source: 10000 PAGE09 runs

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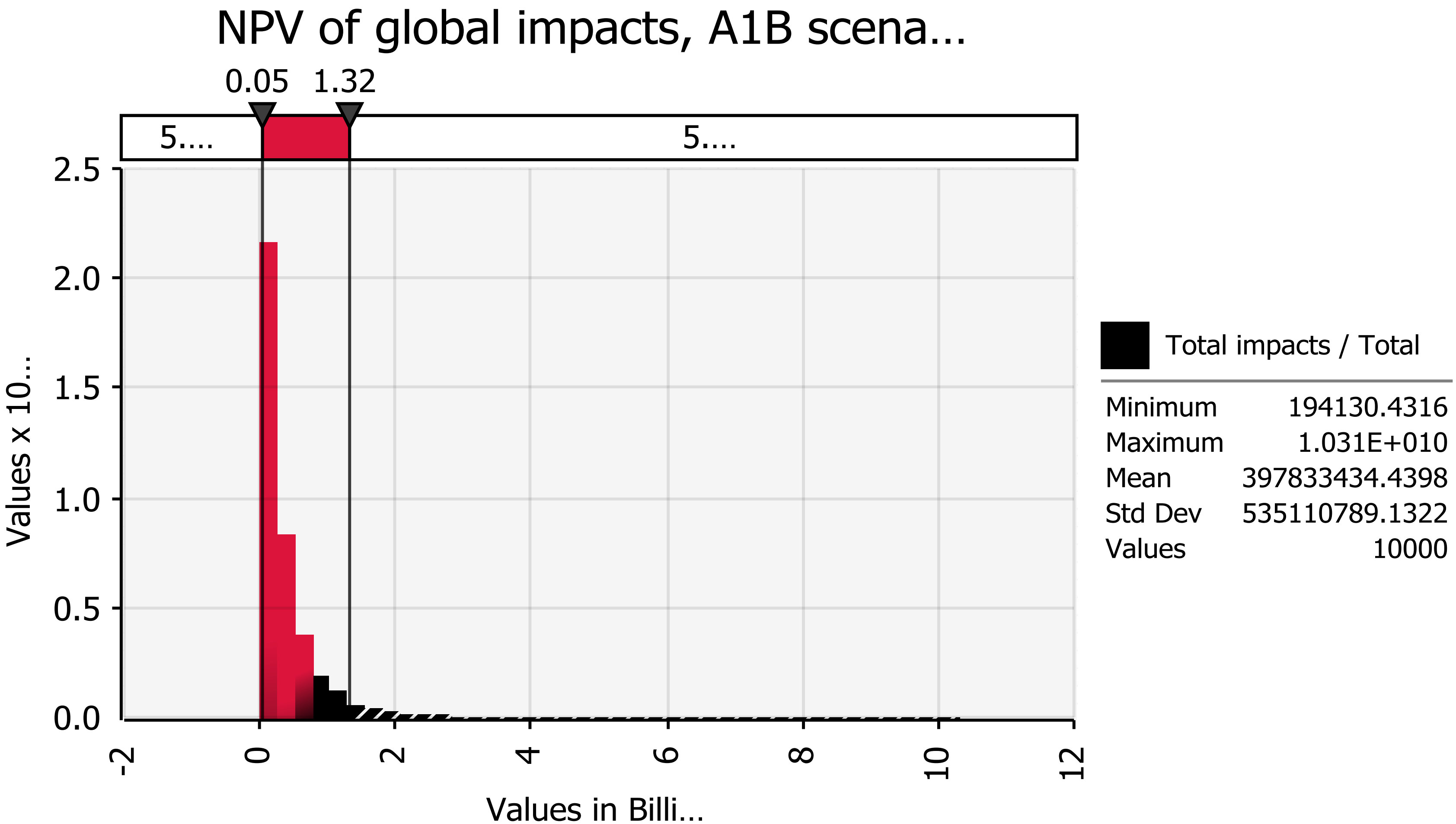

Source: 10000 PAGE09 runs; A1B scenario

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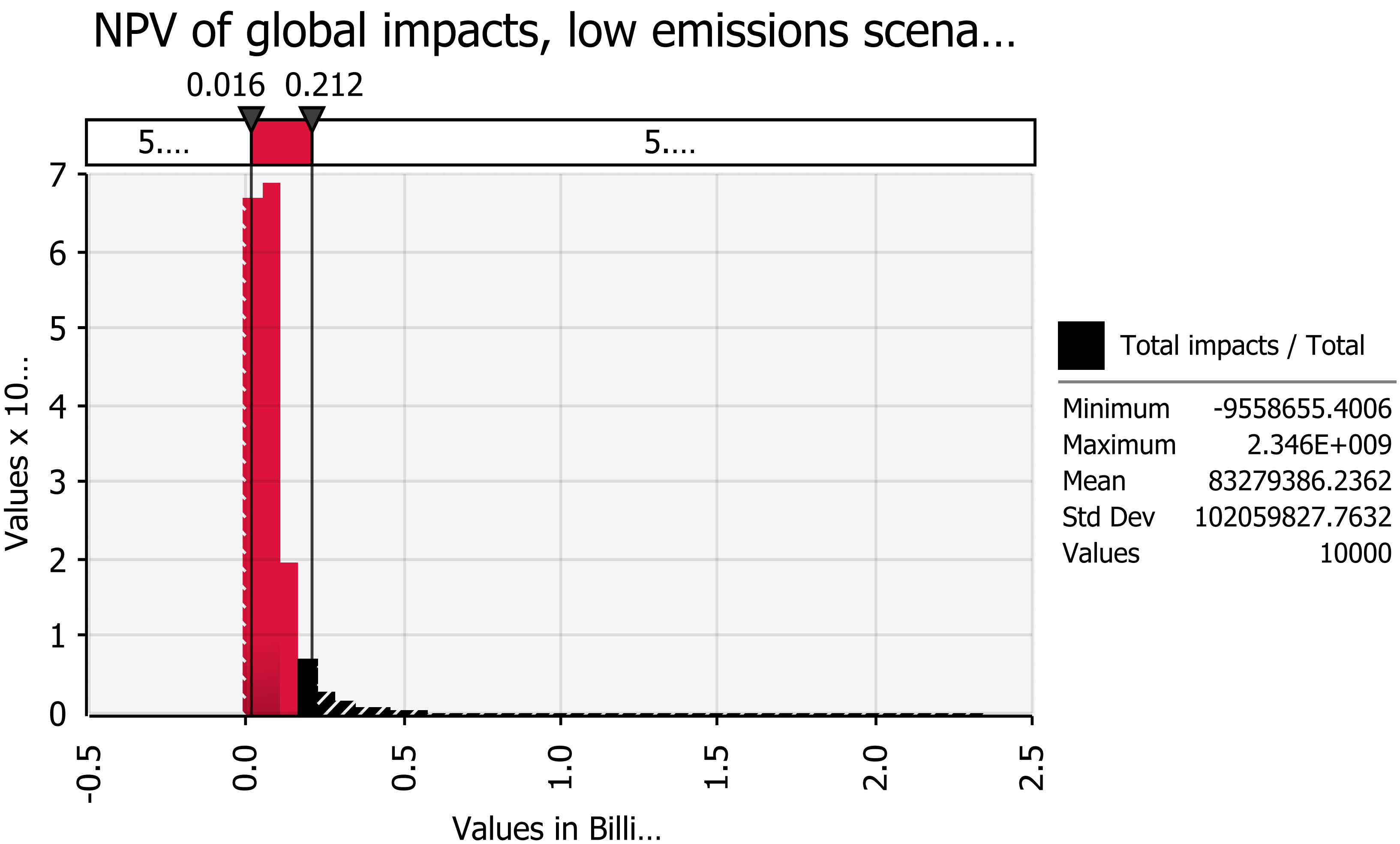

Source: 10000 PAGE09 runs; 2016 r5 low scenario

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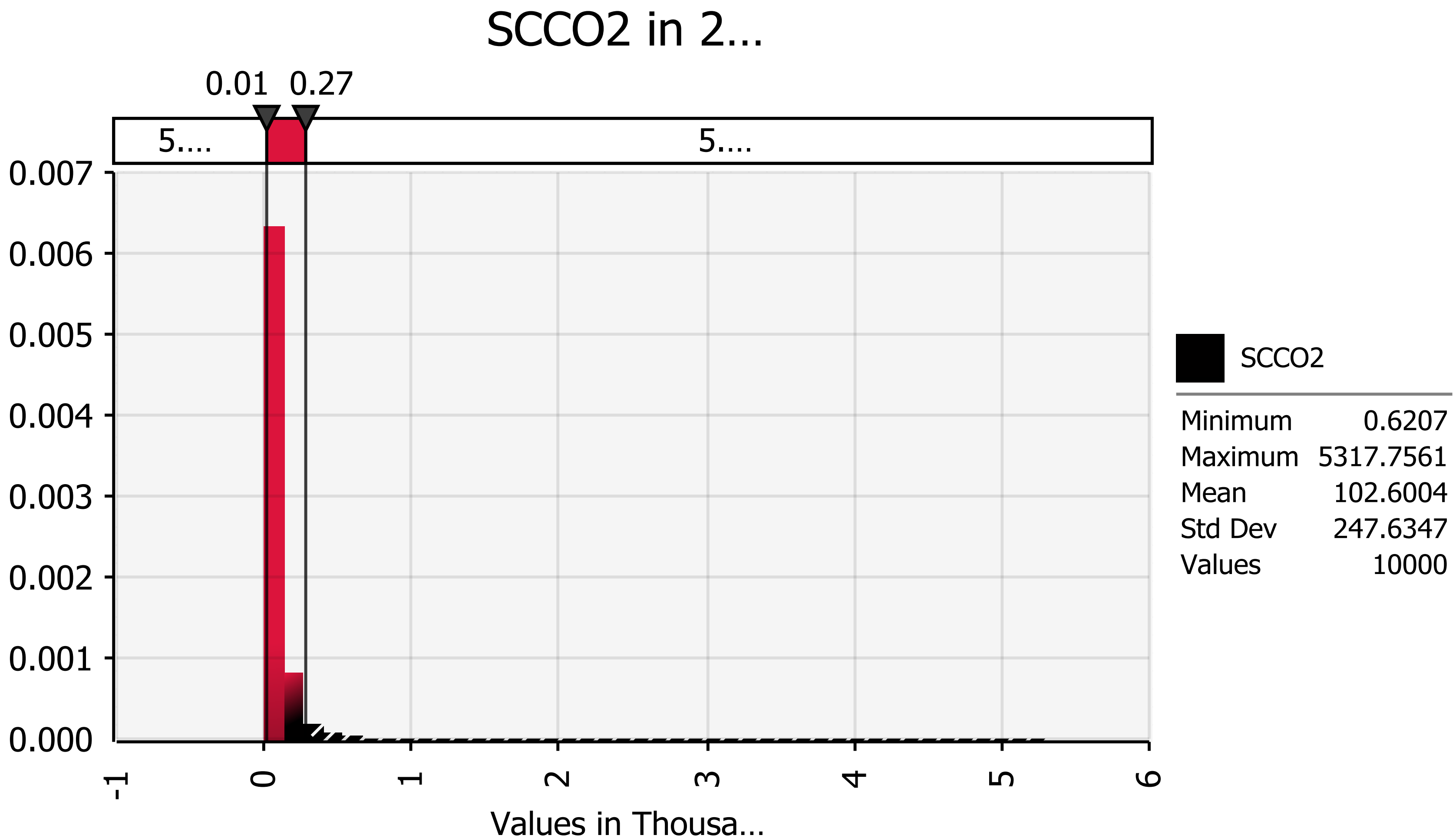
Social cost of CO2, A1B scenario



Source: 10000 PAGE09 runs; A1B scenario

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The social cost of CO_2 in 2010

2010 - 2200	*$US (2005) per tonne*		
	5%	**mean**	**95%**
A1B Scenario	10	100	270
Low emissions	10	45	120

Source: 10000 PAGE09 model runs

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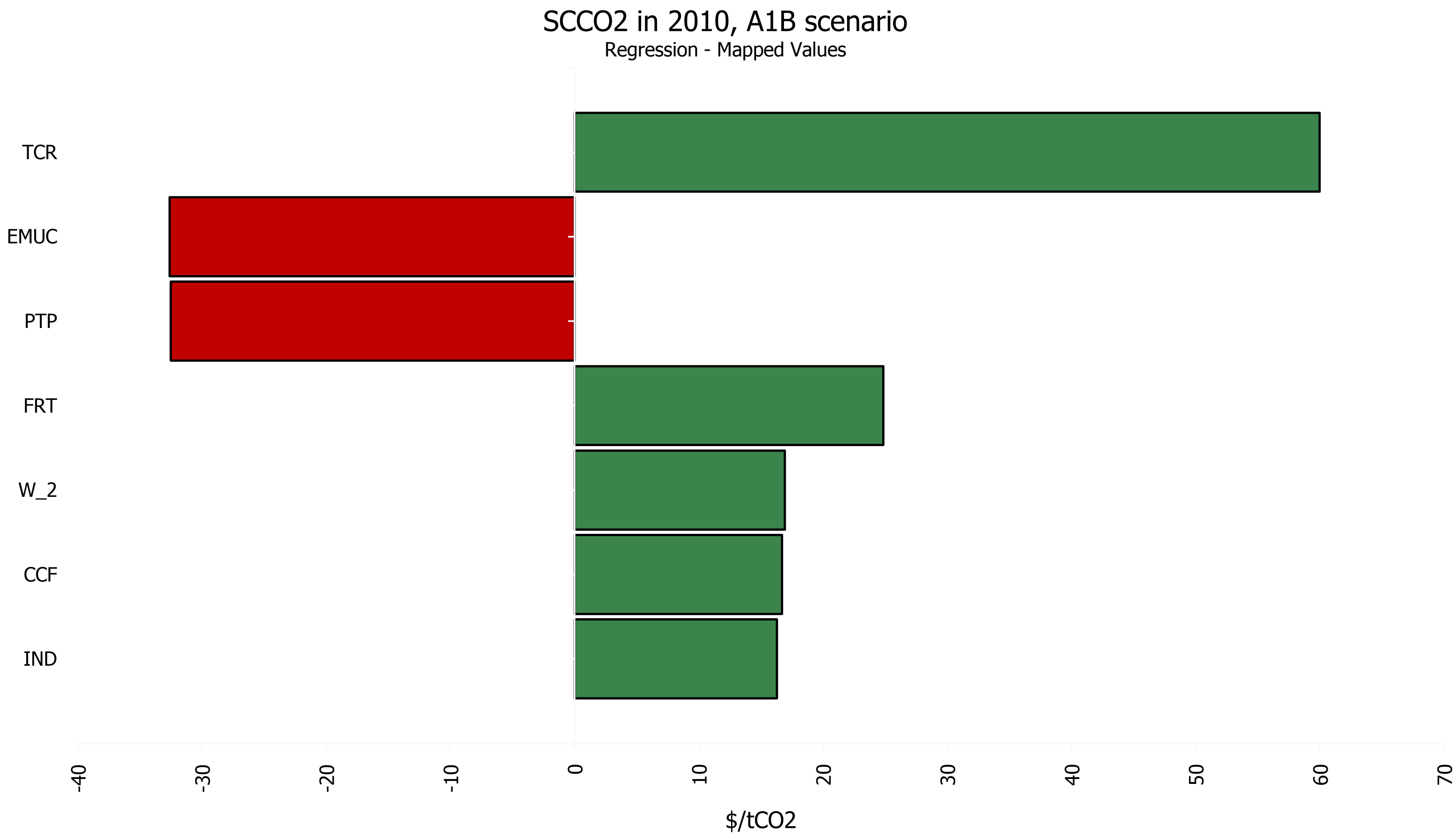
Major influences on the SCCO2



Source: 10000 PAGE09 runs; A1B scenario

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Comparison with results from PAGE2002

SCCO2 in PAGE09 and PAGE2002

2010 - 2200		*$US per tonne CO2*	
	5%	**mean**	**95%**
PAGE09	10	100	270
PAGE2002	3	28	85

Source: 10000 PAGE09 and PAGE2002 model runs; A1B scenario

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Why is the SCCO2 so much greater in PAGE09?

- Normalised to EU base year GDP/capita.
- Less effective adaptation.
- Higher chance of a discontinuity.
- Proper accounting for very large impacts.
- $2005 not $2000.

Supporting documents

The PAGE09 model: A technical description

Describes the changes to the science, impacts, abatement costs and adaptation. Appendices with all the equations and default inputs.

The Social Cost of CO2 from the PAGE09 model

Default inputs and first impact results from the model

PAGE09 v1.7 user guide

Contains brief instructions on using the model

FUND – Climate Framework for Uncertainty, Negotiation and Distribution

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4 November 2010

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FUND (the Climate Framework for Uncertainty, Negotiation and Distribution) is an integrated assessment model linking projections of populations, economic activity and emissions to simple greenhouse gas cycle, climate and sea-level rise models, and to a model predicting and monetizing welfare impacts. Climate change welfare impacts are monetized in 1995 dollars and are modelled over 16 regions. Modelled welfare impacts include agriculture, forestry, sea level rise, cardiovascular and respiratory disorders influenced by cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption from heating and cooling, water resources, unmanaged ecosystems and tropical and extratropical storms (Link and Tol, 2004). The source code, data, and a technical description of the model can be found at http://www.fund-model.org.

Essentially, *FUND* consists of a set of exogenous scenarios and endogenous perturbations. The model distinguishes 16 major regions of the world, viz. the United States of America, Canada, Western Europe, Japan and South Korea, Australia and New Zealand, Central and Eastern Europe, the former Soviet Union, the Middle East, Central America, South America, South Asia, Southeast Asia, China, North Africa, Sub-Saharan Africa, and Small Island States. Version 3.6, the latest version, runs to the year 3000 in time steps of one year.

The period of 1950-1990 is used for the calibration of the model, which is based on the *IMAGE* 100-year database (Batjes and Goldewijk, 1994). The period 1990-2000 is based on observations (http://earthtrends.wri.org). The 2000-2010 period is interpolated from the immediate past. The climate scenarios for the period 2010-2100 are based on the EMF14 Standardized Scenario, which lies somewhere in between IS92a and IS92f (Leggett *et al.*, 1992). The period 2100-3000 is extrapolated.

The scenarios are defined by varied rates of population growth, economic growth, autonomous energy efficiency improvements, and decarbonization of energy use (autonomous carbon efficiency improvements), as well as by emissions of carbon dioxide from land use change, methane emissions, and nitrous oxide emissions. FUND 3.5 introduced a dynamic biosphere feedback component that perturbates carbon dioxide emissions based on temperature changes.

Emission reduction of carbon dioxide, methane and nitrous oxide is specified as in Tol (2006). Simple cost curves are used for the economic impact of abatement, with limited scope for endogenous technological progress and interregional spillovers (Tol, 2005).

The scenarios of economic growth are perturbed by the effects of climatic change. Climate-induced migration between the regions of the world causes the population sizes to change. Immigrants are assumed to assimilate immediately and completely with the respective host population.

The tangible welfare impacts are dead-weight losses to the economy. Consumption and investment are reduced without changing the savings rate. As a result, climate change reduces long-term economic growth, although consumption is particularly affected in the short-term. Economic growth is also reduced by carbon dioxide abatement measures. The energy intensity of the economy and the carbon intensity of the energy supply autonomously decrease over time. This process can be accelerated by abatement policies.

The endogenous parts of *FUND* consist of the atmospheric concentrations of carbon dioxide, methane and nitrous oxide, the global mean temperature, the effect of carbon dioxide emission reductions on the economy and on emissions, and the effect of the damages on the economy caused by climate change. Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted. The atmospheric concentration of carbon dioxide, measured in parts per million by volume, is represented by the five-box model of Maier-Reimer and Hasselmann (1987). Its parameters are taken from Hammitt *et al*. (1992).

The radiative forcing of carbon dioxide, methane, nitrous oxide and sulphur aerosols is determined based on Shine *et al*. (1990). The global mean temperature, *T*, is governed by a geometric build-up to its equilibrium (determined by the radiative forcing, *RF*), with a half-life of 50 years. In the base case, the global mean temperature rises in equilibrium by 3.0°C for a doubling of carbon dioxide equivalents. Regional temperature is derived by multiplying the global mean temperature by a fixed factor, which corresponds to the spatial climate change pattern averaged over 14 GCMs (Mendelsohn *et al.*, 2000). The global mean sea level is also geometric, with its equilibrium level determined by the temperature and a half-life of 50 years. Both temperature and sea level are calibrated to correspond to the best guess temperature and sea level for the IS92a scenario of Kattenberg *et al.* (1996).

The climate welfare impact module, based on Tol (2002a; Tol, 2002b) includes the following categories: agriculture, forestry, sea level rise, cardiovascular and respiratory disorders influenced by cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption from heating and cooling, water resources, unmanaged ecosystems and tropical and extratropical storms. Climate change related damages are triggered by either the rate of temperature change (benchmarked at 0.04°C/yr) or the level of temperature change (benchmarked at 1.0°C). Damages from the rate of temperature change slowly fade, reflecting adaptation (cf. Tol, 2002b).

In the model individuals can die prematurely due to temperature stress or vector-borne diseases, or they can migrate because of sea level rise. Like all welfare impacts of climate change, these effects are monetized. The value of a statistical life is set to be 200 times the annual per capita income.[1] The resulting value of a statistical life lies in the middle of the observed range of values in the literature (cf. Cline, 1992). The value of emigration is set to be three times the per capita income (Tol, 1995; Tol, 1996), the value of immigration is 40 per cent of the per capita income in the host region (Cline, 1992). Losses of dryland and wetlands due to sea level rise are modelled explicitly. The monetary value of a loss of one square kilometre of dryland was on average $4 million in OECD countries in 1990 (cf. Fankhauser, 1994). Dryland value is assumed to be proportional to GDP per square kilometre. Wetland losses are according to estimates from Brander et al. (2006). Coastal protection is based on cost-benefit analysis, including the value of additional wetland lost due to the construction of dikes and subsequent coastal squeeze.

Other welfare impact categories, such as agriculture, forestry, hurricanes, energy, water, and ecosystems, are directly expressed in monetary values without an intermediate layer of impacts measured in their 'natural' units (cf. Tol, 2002a). Modelled effects of climate change on energy consumption, agriculture, and cardiovascular and respiratory diseases explicitly recognize that there is a climatic optimum, which is determined by a variety of factors, including plant physiology and the behaviour of farmers. Impacts are positive or negative depending on whether the actual climate conditions are moving closer to or away from that optimum climate. Impacts are larger if the initial climate conditions are further away from the optimum climate. The optimum climate is of importance with regard to the potential impacts. The actual impacts lag behind the potential

[1] Note that this implies that the monetary value of health risk is effectively discounted with the pure rate of time preference rather than with the consumption rate of discount (Horowitz, 2002). It also implies that, after equity weighing, the value of a statistical life is equal across the world (Fankhauser *et al.*, 1997).

impacts, depending on the speed of adaptation. The impacts of not being fully adapted to new climate conditions are always negative (cf. Tol, 2002b).

The welfare impacts of climate change on coastal zones, forestry, hurricanes, unmanaged ecosystems, water resources, diarrhoea, malaria, dengue fever, and schistosomiasis are modelled as simple power functions. Impacts are either negative or positive, and they do not change sign (cf. Tol, 2002b).

Vulnerability to climate change changes with population growth, economic growth, and technological progress. Some systems are expected to become more vulnerable, such as water resources (with population growth) and heat-related disorders (with urbanization), or more valuable, such as ecosystems and health (with higher per capita incomes). Other systems are projected to become less vulnerable, such as energy consumption (with technological progress), agriculture (with economic growth) and vector- and water-borne diseases (with improved health care) (cf. Tol, 2002b).

In the Monte Carlo analyses, most model parameters (including parameters for the physical components as well as the economic valuation components) are varied. The probability density functions are mostly based on expert guesses, but where possible "objective" estimates were used. Parameters are assumed to vary independently of one another, except when there are calibration or accounting constraints. "Preference parameters" like the discount rate or the parameter of risk aversion are not varied in the Monte Carlo analysis. Details of the Monte Carlo analysis can be found on *FUND*'s website at http://www.fund-model.org.

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The FUND model

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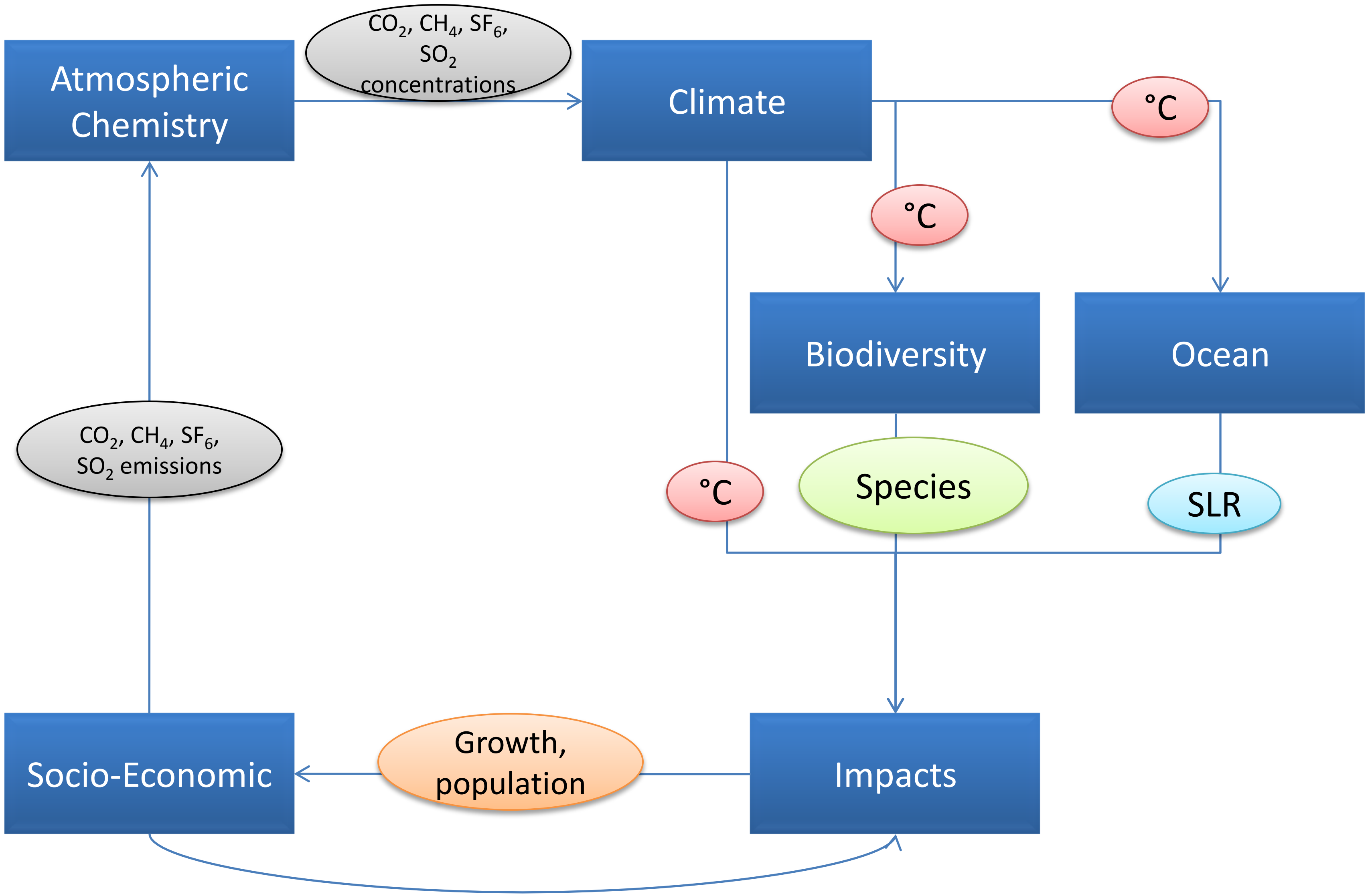
Outline

- FUND model
  - Basic structure
  - Impacts
  - Planed model developments
- Catastrophes
- Social Cost of Carbon – WG

FUND


Atmospheric Chemistry
CO_2, CH_4, SF_6, SO_2 concentrations
Climate
°C
°C
Biodiversity
Ocean
CO_2, CH_4, SF_6, SO_2 emissions
°C
Species
SLR
Socio-Economic
Growth, population
Impacts

Scenario

Exogenous

- GDP
- Population
- Energy and carbon intensity
- Land use change and deforestation CO_2 emissions
- CH_4 emissions
- NO_2 emissions

Endogenous

- CO_2 emissions
- CO_2 emissions from "dynamic biosphere"
- SF_6 emissions
- SO_2 emissions

Physical Components

- All gas cycles explicitly modeled (CO_2, CH_4, N_2O, SO_2)
- RF for each gas explicitly modeled

- Climate Sensitivity Uncertain
- Adjust transient climate response properly!

Health Impacts

Mortality (#)

Vector born diseases
- Dengue fever
- Malaria
- Schistosomiasis

Diarrhoea
Cardiovascular
- Cold
- Heat

Respiratory
Extratropical storms
Tropical storms

Morbidity (years)

Vector born diseases
- Dengue fever
- Malaria
- Schistosomiasis

Diarrhoea
Cardiovascular
- Cold
- Heat

Respiratory

Value of a Statistical Life

WTP

Sea-level Rise

- Based on Fankhauser (1994), updated

- Cost of protection
- Value of lost dryland
- Value of lost wetland
- Cost of Emigration
- Cost of Imigration

More Impacts

- Agriculture
- Tropical Storms
- Extratropical Storms
- Forestry
- Heating Energy
- Cooling Energy
- Water Resources
- Species Loss

Damages

$$D_{tr} = \sum_{s} D_s(T_{tr}, y_{tr}, \ldots)$$

$$\begin{cases} \gamma = 0 & \text{additive damage} \\ \gamma = 1 & \text{multiplicative damage} \\ \gamma > 1 & \text{"luxury good" type damage} \\ \gamma < 0 & \text{"Schelling" type damage} \end{cases}$$

$$D_s(T, y, \ldots) = \alpha \left(\frac{T}{1.0}\right)^{\epsilon} \left(\frac{y}{y_0}\right)^{\gamma}$$

Uncertain in Monte Carlo mode

Future Plans on Impacts

- Ocean Acidification
  - Corral reefs
  - Shell fish
- Tourism
- River floods
- Update energy consumption

Catastrophes

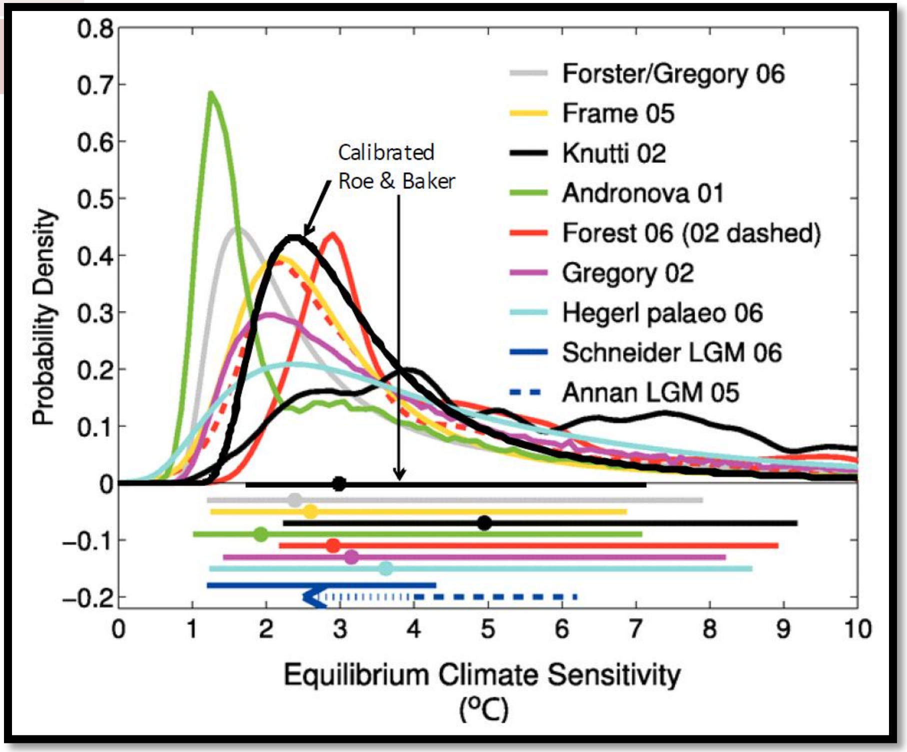
Ceronsky et al. (~~2005~~2010 hopefully!) „Checking the price tag on catastrophe: The social cost of carbon under non-linear climate response," *FNU Working Paper* 87

- Thermohaline circulation collapse
- Marine methane hydrate destabilization
- High Climate Sensitivities

Social Cost of Carbon - WG

Scenario Uncertainty

Scenario	YpC in thousand $	Probability
IMAGE	43.4	20%
MERGE	27.8	20%
MESSAGE	32.1	20%
MiniCAM	42.6	20%
5th Scenario	35.7	20%



Discounting

Distribution

Case 1

Country	Damage
Italy	0.9%
Rwanda	13.2%

Case 2

Country	Damage
Italy	1.0%
Rwanda	1.0%

=

Country	Damage
World Average	1.0%

Anthoff, D. and R. S. J. Tol (2009). "The Impact of Climate Change on the Balanced Growth Equivalent: An Application of FUND.“ *Environmental and Resource Economics* **43**(3): 351-367

Anthoff, D. and R. S. J. Tol (2010). "On international equity weights and national decision making on climate change.“ *Journal of Environmental Economics and Management* **60**(1): 14-20

Thank you!

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Representation of Climate Impacts in GCAM

Leon Clarke

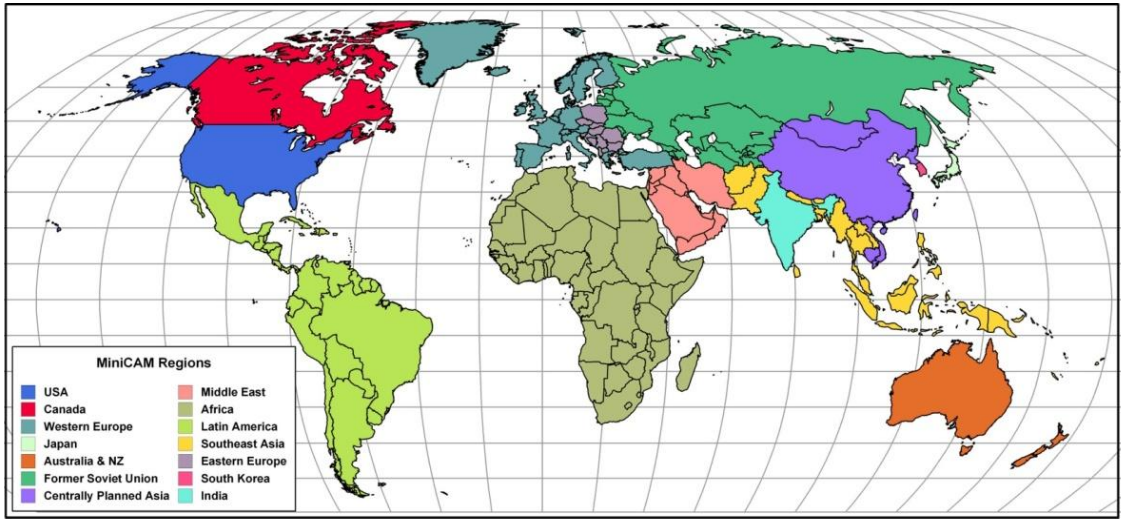
Workshop on Modeling Climate Change Impacts and Associated Economic Damages

Washington DC

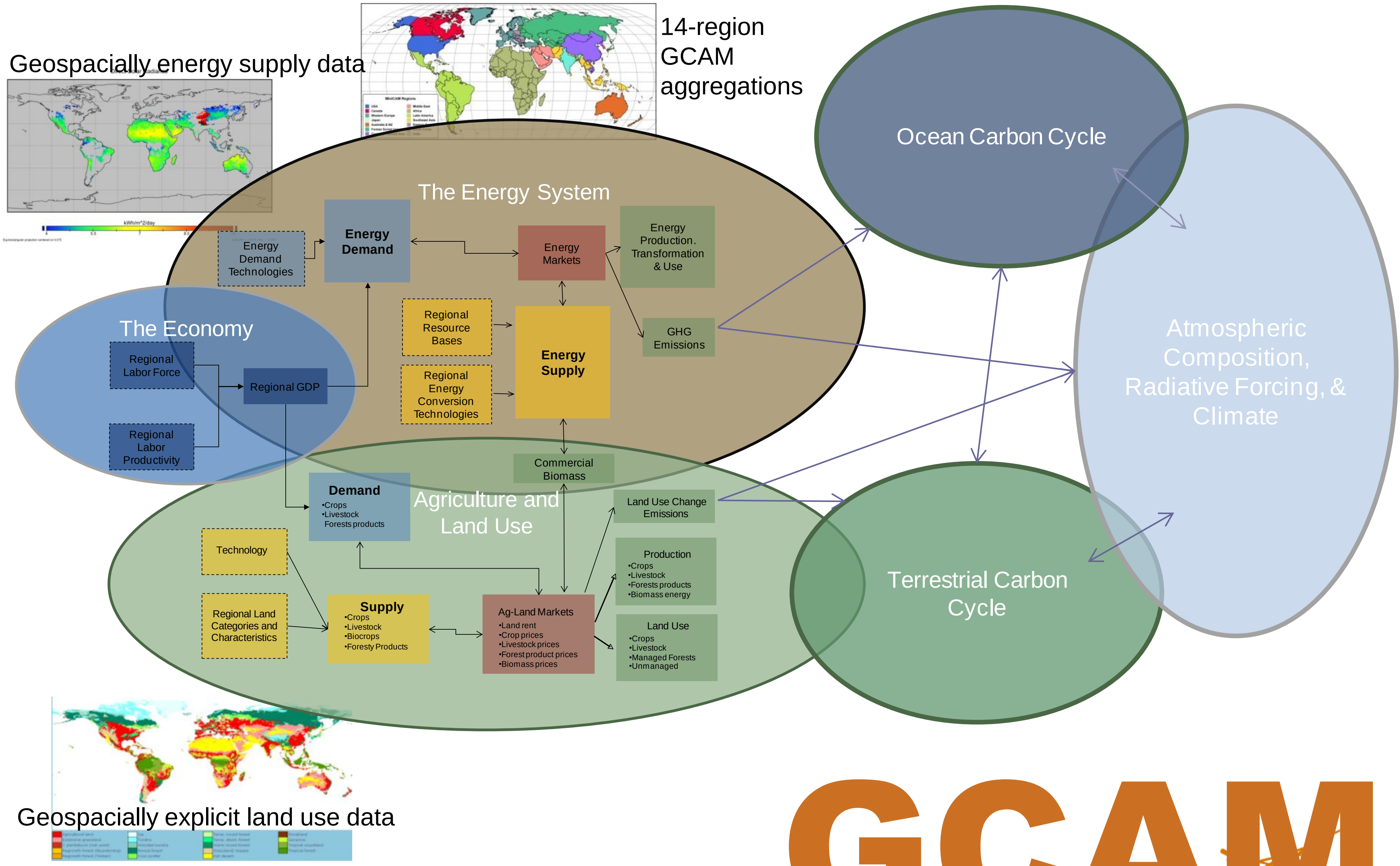
Thursday, November 18, 2010

Pacific Northwest
NATIONAL LABORATORY

What is GCAM?



- Builds on the energy/economy model of Edmonds and Reilly completed three decades ago.
- Combines economics-based energy, agricultural models with an Integrated Climate Assessment Model (MAGICC).
- Dynamic-recursive model.
- Technologically detailed integrated assessment model.
- 14 geopolitical regions
- Emissions of 16 greenhouse gases and short-lived species: CO_2, CH_4, N_2O, halocarbons, carbonacious aerosols, reactive gases, sulfur dioxide.
- Runs through 2095 in 15-year time steps (moving to variable time steps).



GCAM

Pacific Northwest NATIONAL LABORATORY

What impacts would we want to consider in PNNL/JGCRI IA modeling?

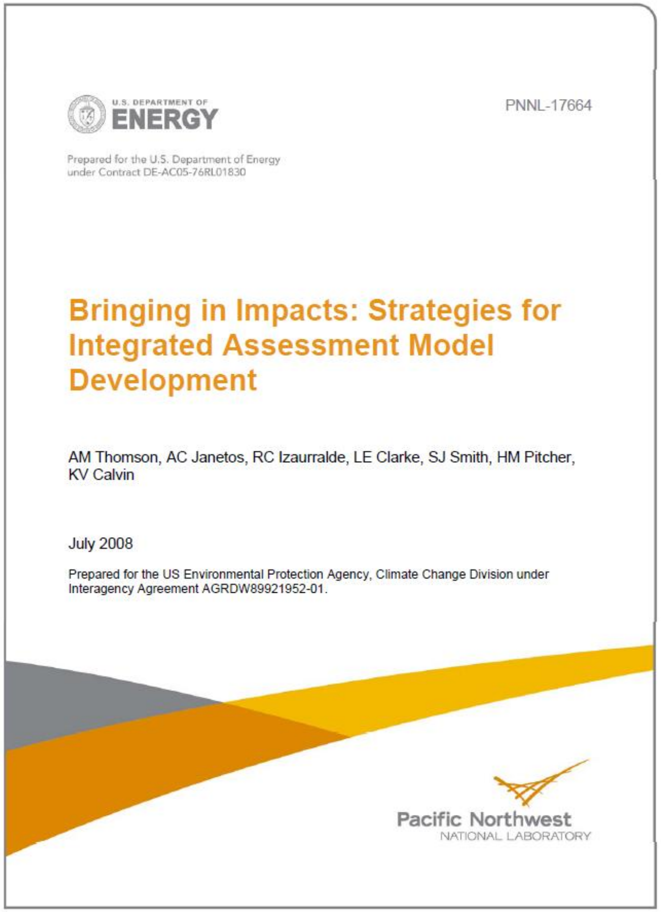
- Goal #1: Pick things that are important.
- Goal #2: Pick things that involve interactions among the various systems represented in IA models
- Goal #3: Pick things that we actually have a chance of doing.

- Expanding on #3: A primary benefit of IA models is their ability capture interactions between systems. This leads to a perspective on impacts in which we distinguish between
  - Those which are most amenable to an integrated perspective.
  - Those which can "hang" off of the model and not feed back to other systems in the model.

- Although integrated analysis brings impacts together in an integrated system, aggregating and monetizing all impacts is not inherently core to considering impacts in GCAM.

A Plan for Impacts in PNNL/JGCRI's IA Modeling

- Near-term priorities;
  - Agriculture, Forestry, Land Use and Land Cover
  - Energy Use
  - Ocean Acidification
- High priorities with substantial model development necessary
  - Water Resources
  - Sea-Level Rise and Coastal Impacts
  - Human Health and Demographics
- Of substantial interest, but not easily quantifiable within existing IA models
  - Extreme Events and Thresholds
  - Biodiversity


U.S. DEPARTMENT OF ENERGY

PNNL-17664

Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830

Bringing in Impacts: Strategies for Integrated Assessment Model Development

AM Thomson, AC Janetos, RC Izaurralde, LE Clarke, SJ Smith, HM Pitcher, KV Calvin

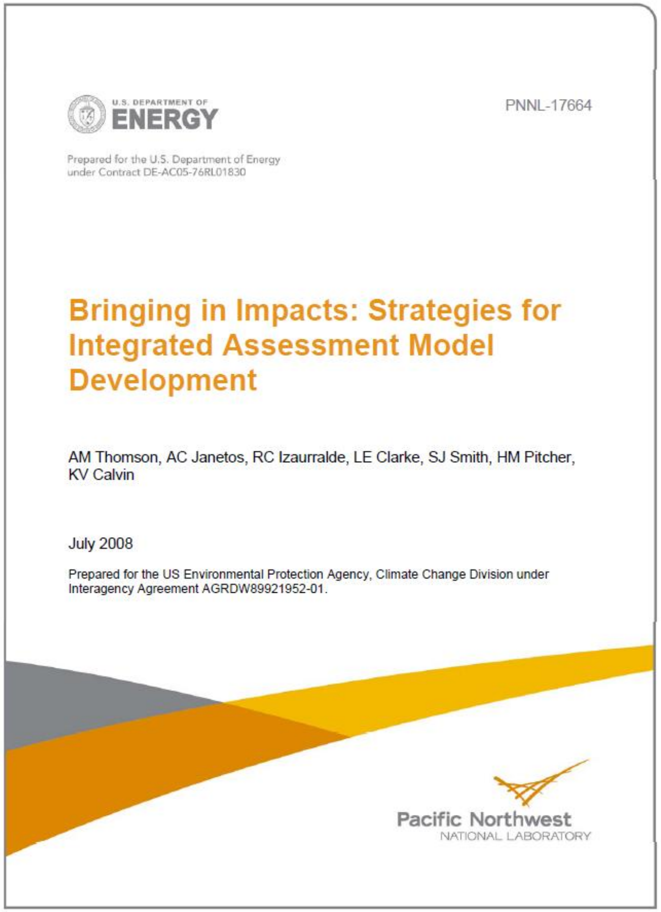
July 2008

Prepared for the US Environmental Protection Agency, Climate Change Division under Interagency Agreement AGRDW89921952-01.

Pacific Northwest NATIONAL LABORATORY

A Plan for Impacts in PNNL/JGCRI's IA Modeling

- There are many ways to pursue these impacts:
  - One dimension
    - All in GCAM.
    - Linkages to other models (iESM, regional initiatives).
  - Another dimension
    - Endogenous interactions within the model – feedbacks with other systems.
    - "Hanging" off of GCAM.


U.S. DEPARTMENT OF ENERGY

PNNL-17664

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Bringing in Impacts: Strategies for Integrated Assessment Model Development

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July 2008

Prepared for the US Environmental Protection Agency, Climate Change Division under Interagency Agreement AGRDW89921952-01.

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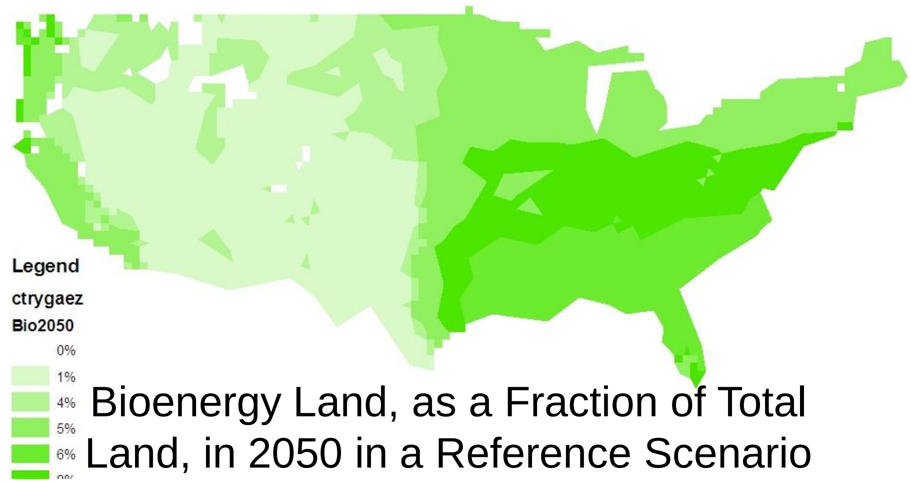
Land Use Impacts

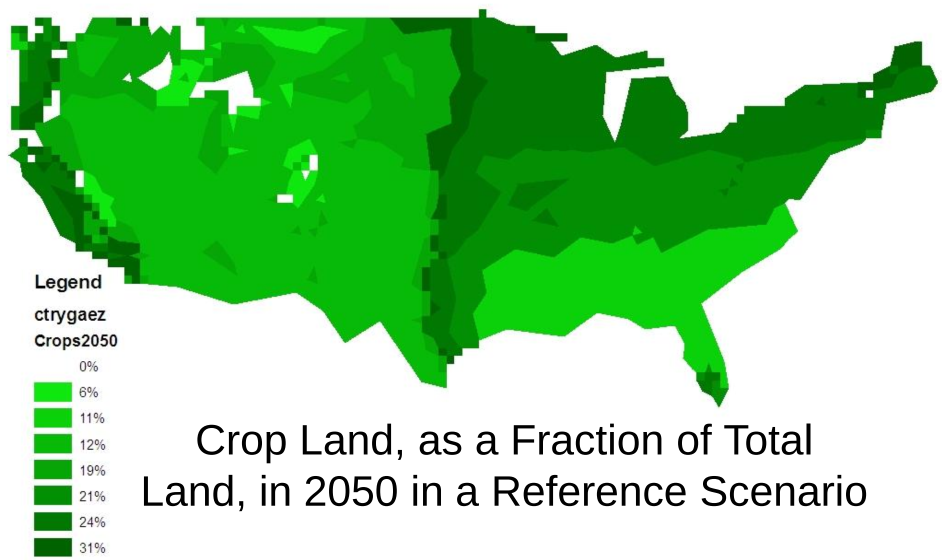
GCAM Moving to an Agro Ecological Zone Formulation for AgLU

OPTIONS FOR FEEDBACK

- Link results from ecosystem models (EPIC/BIOME/CENTURY) and ESMs to GCAM by changing parameters.
- Use sensitivity studies to begin to develop a concept of the scale of impacts in the context of integrated assessment and adjust GCAM parameters.
- Develop a reduced-form representation of ecosystem processes and response to climate change in GCAM.

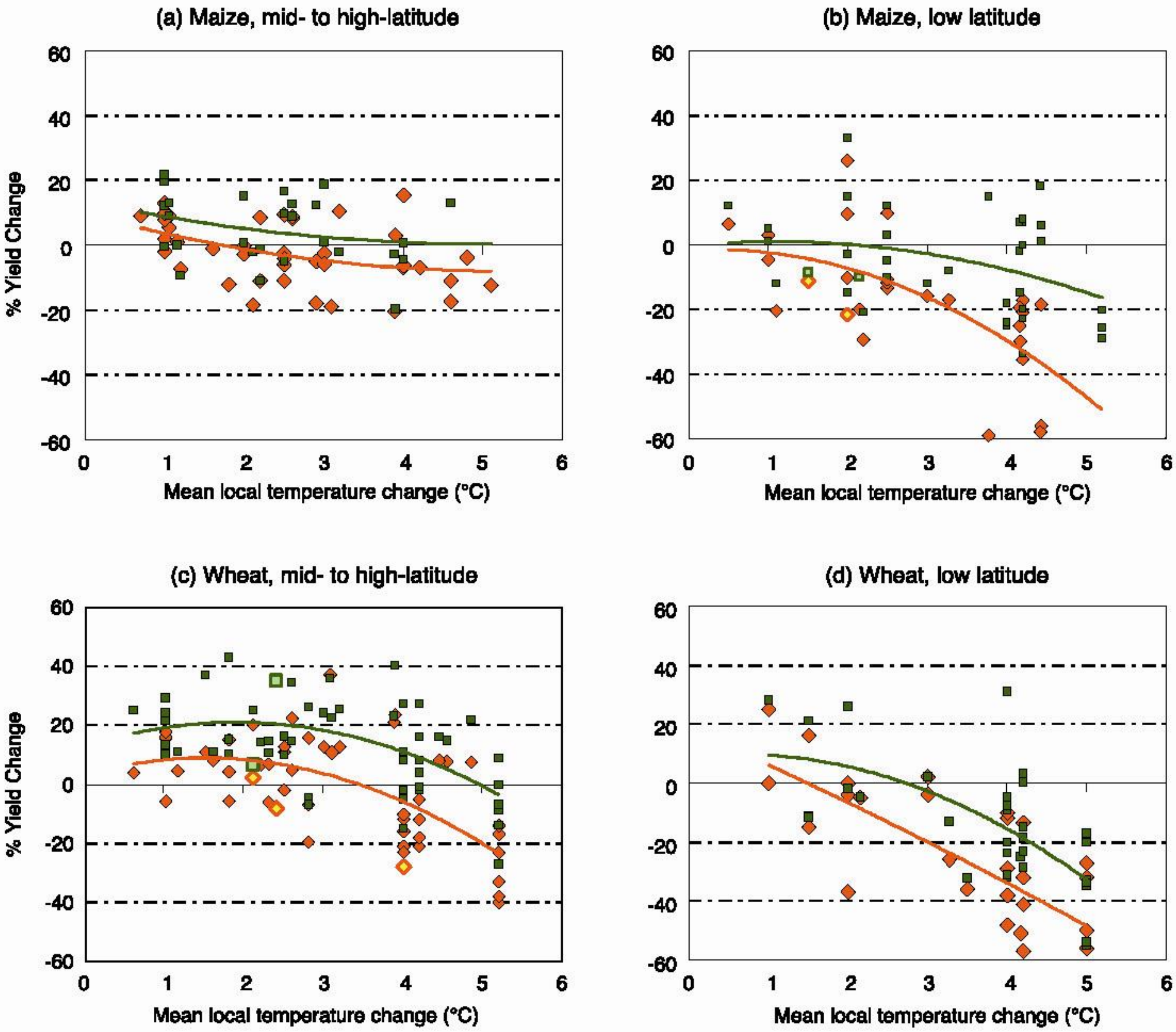


Bioenergy Land, as a Fraction of Total Land, in 2050 in a Reference Scenario



Crop Land, as a Fraction of Total Land, in 2050 in a Reference Scenario

Synthesis of process-level impact studies



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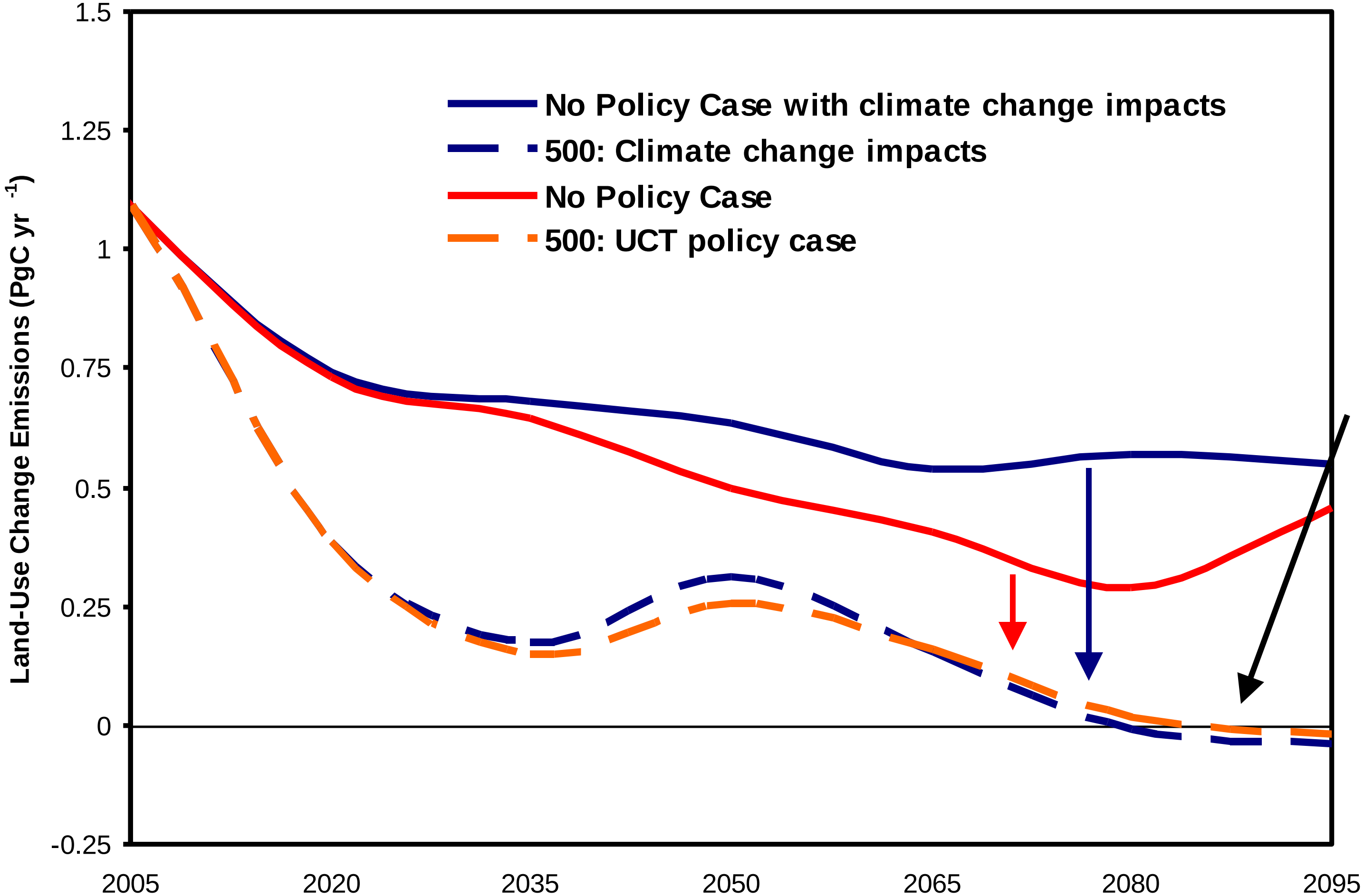
Climate impacts interact with mitigation policy.



By 2095, ILUC emissions go below 0 with climate policy cases

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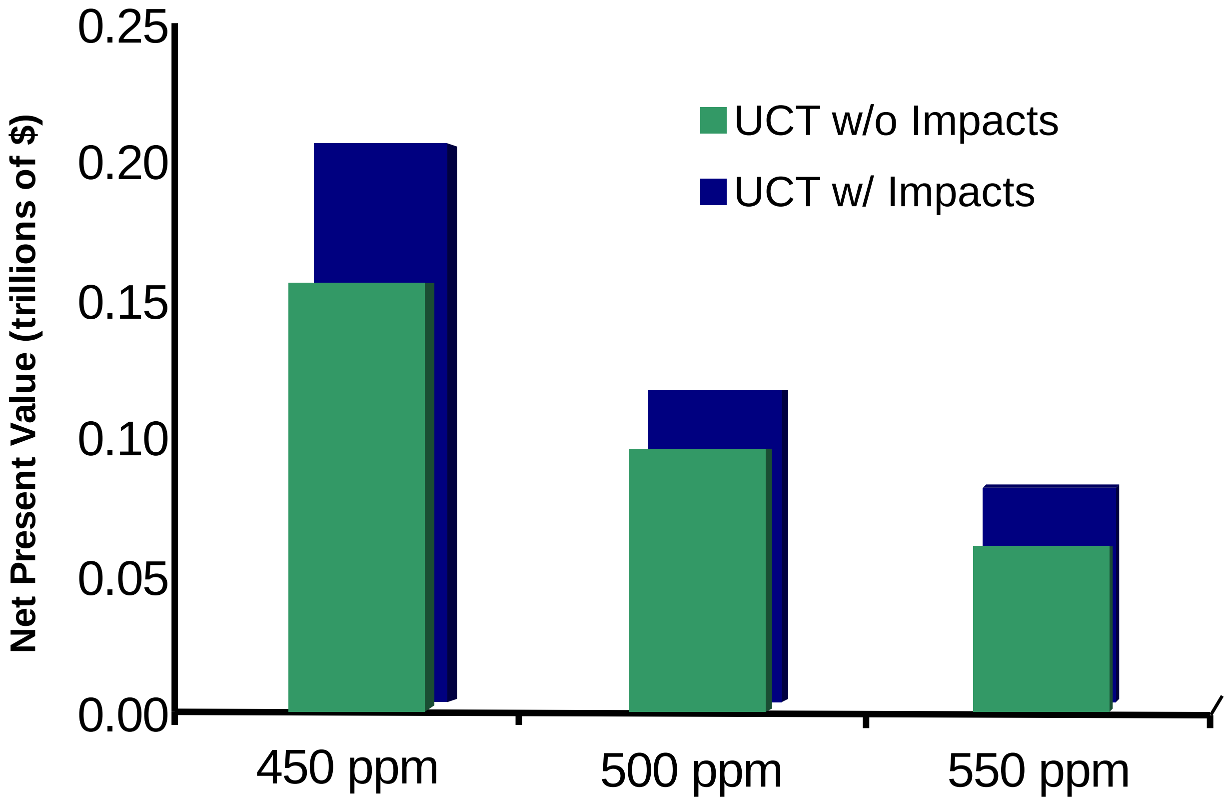
Impact of Impacts on Costs of Mitigation



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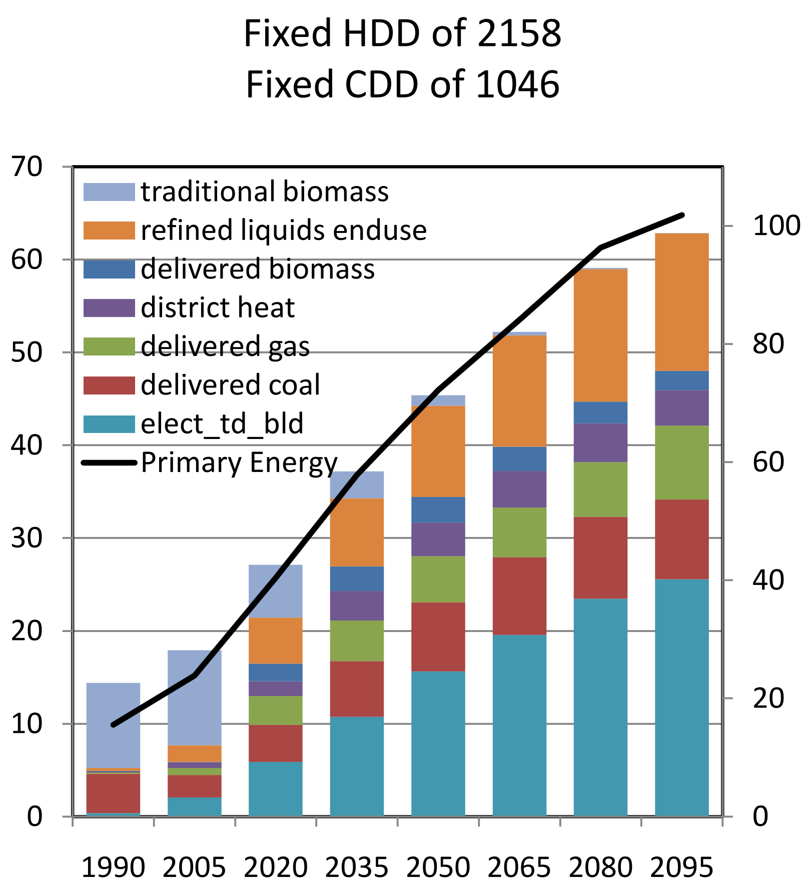
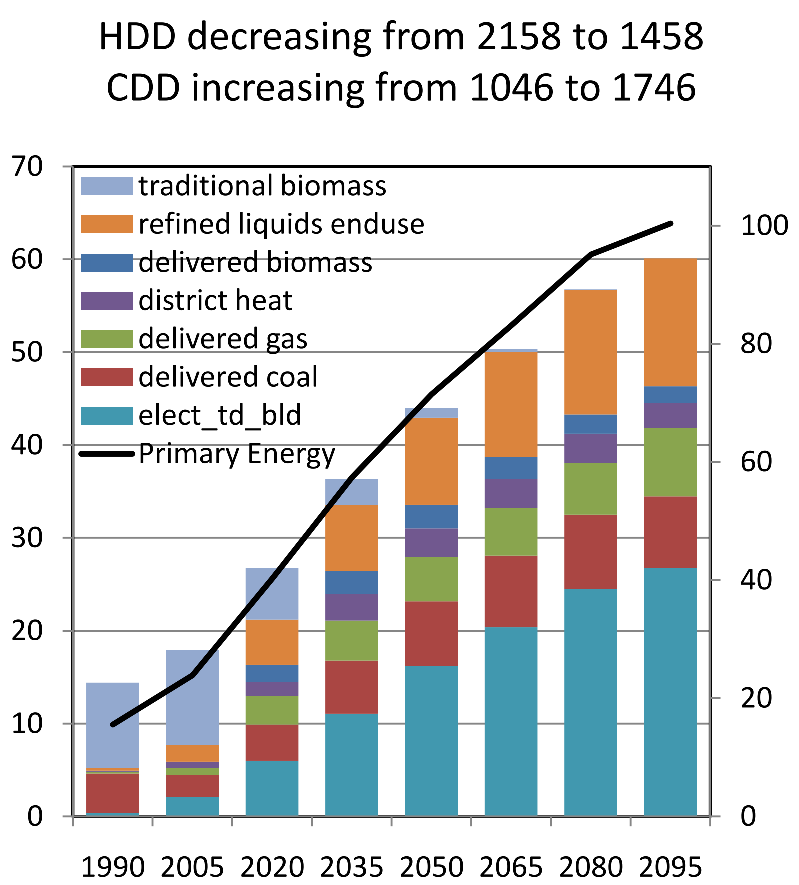
Energy Impacts

Effects of Changing Degree Days on Building Energy Consumption:
The Reference Case of China Buildings





Other Long-Term Options: (1) Feedbacks on power plant efficiencies, (2) Feedbacks on water supply for hydroelectric power.

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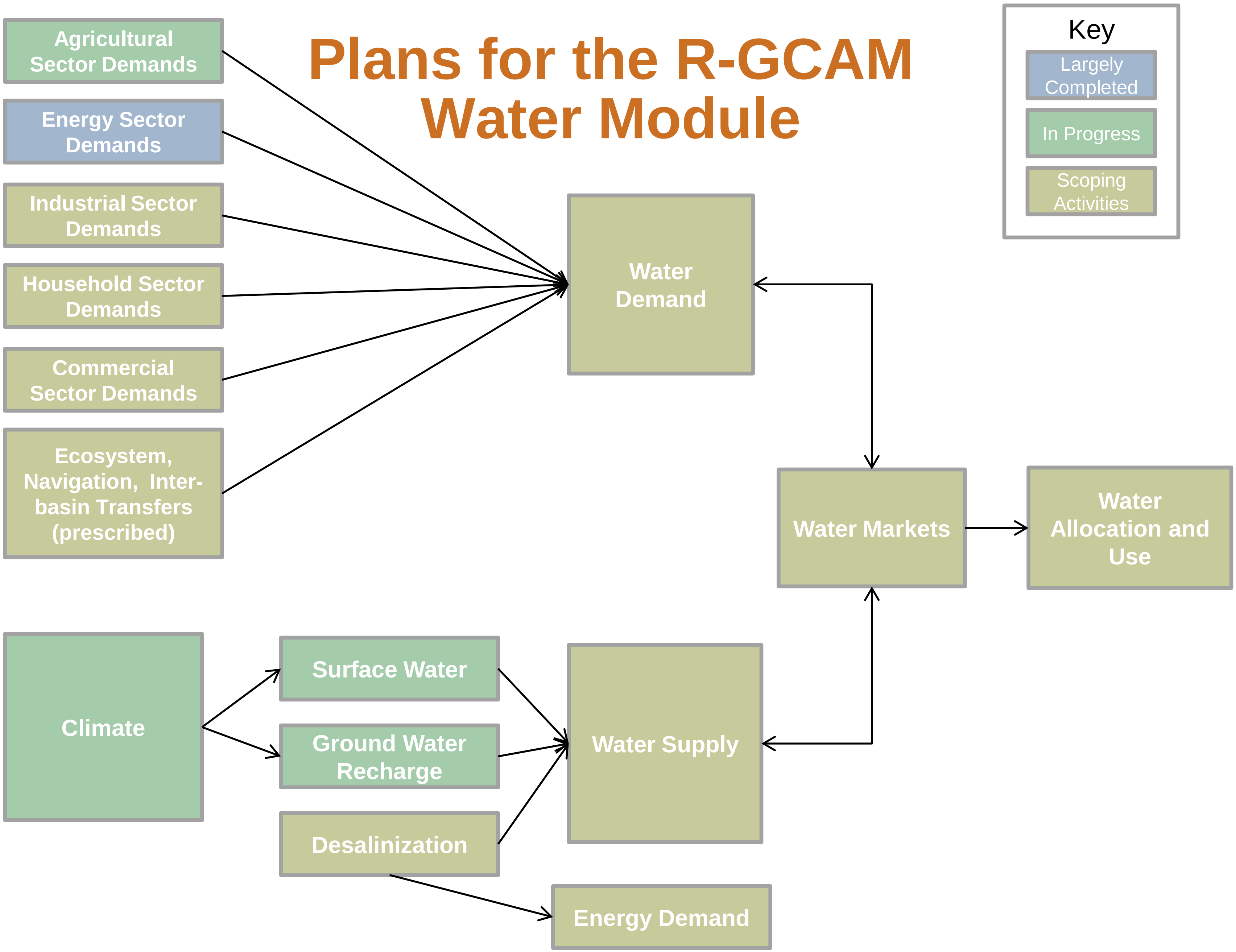
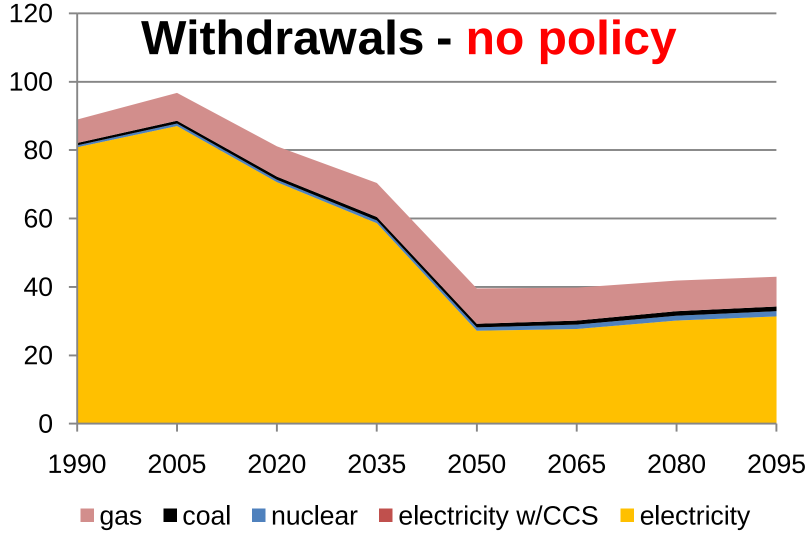
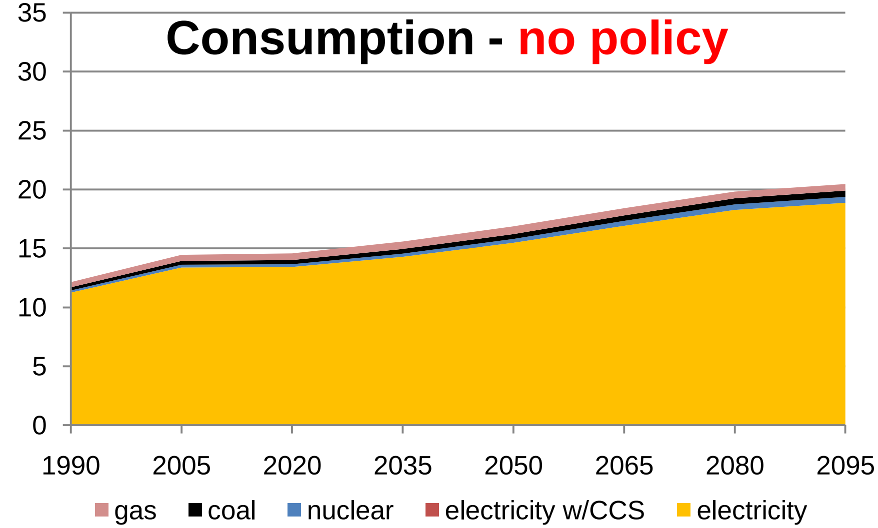
Water

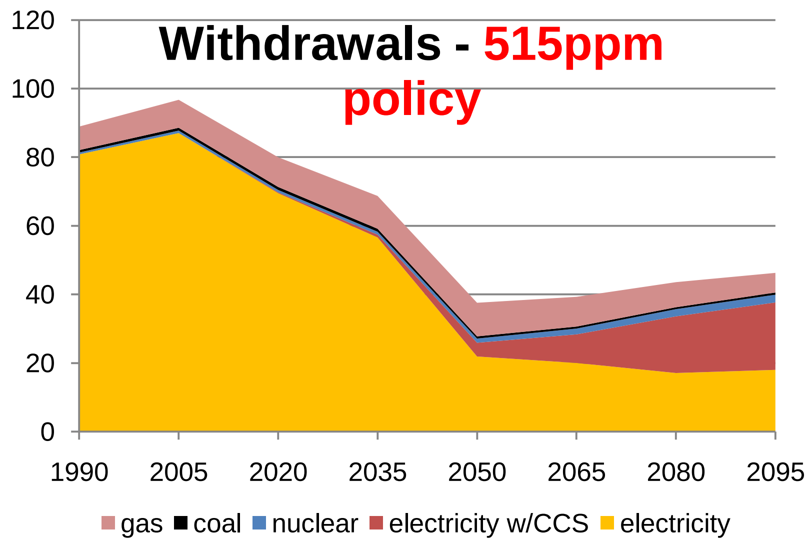
Plans for the R-GCAM Water Module

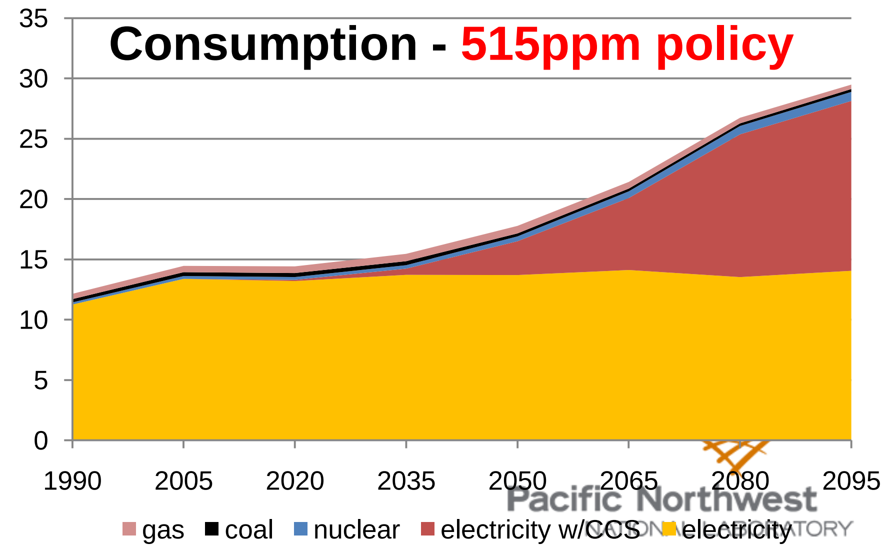


GCAM: U.S. Energy System Results









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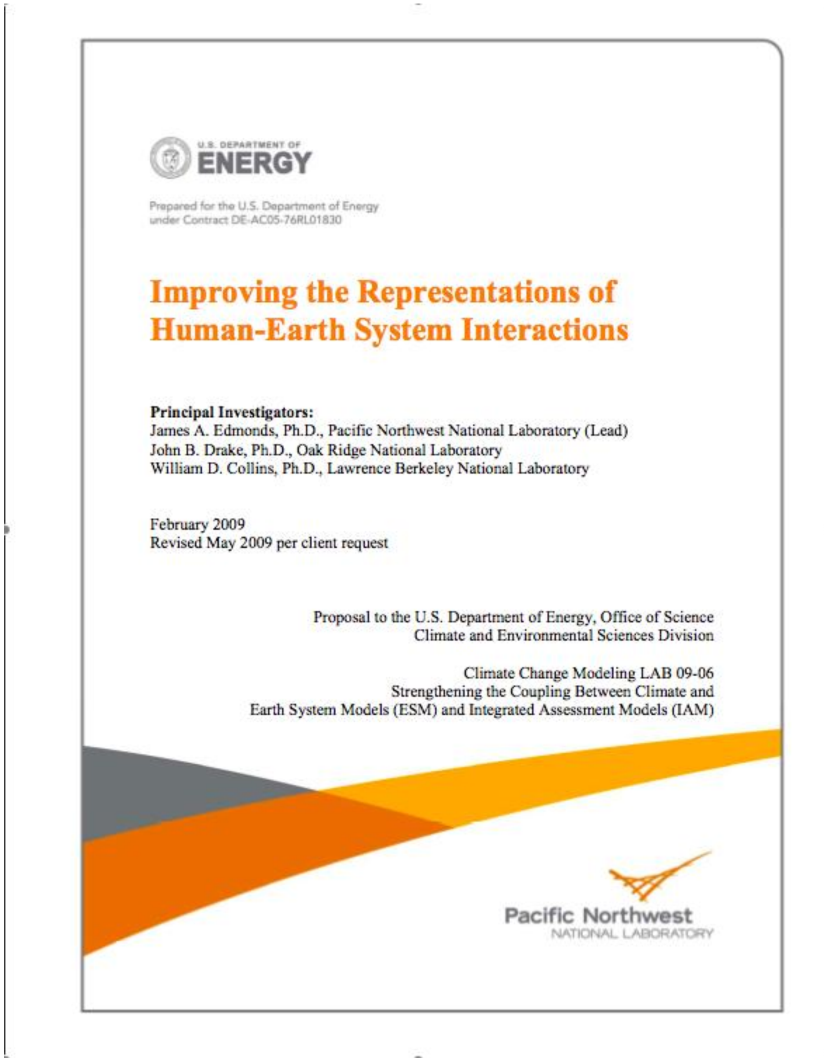
Examples of Linkages between Platforms: iESM

A Research Collaboration Between Three National Laboratories: PNNL, ORNL and LBNL



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Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

Improving the Representations of Human-Earth System Interactions

Principal Investigators:
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John B. Drake, Ph.D., Oak Ridge National Laboratory
William D. Collins, Ph.D., Lawrence Berkeley National Laboratory

February 2009
Revised May 2009 per client request

Proposal to the U.S. Department of Energy, Office of Science
Climate and Environmental Sciences Division

Climate Change Modeling LAB 09-06
Strengthening the Coupling Between Climate and
Earth System Models (ESM) and Integrated Assessment Models (IAM)

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Three Primary Tasks

- **Create a first generation integrated Earth System Model (iESM)** with both the human components of an IAM and a physical ESM;
- Further **develop components and linkages** within the iESM and apply the model to improve our understanding of the coupled physical, ecological, and human system;
- **Add realistic hydrology**, including freshwater demand, allocations, and demands to hold stocks of water as well as representations of freshwater availability from surface water, ground water, and desalinization

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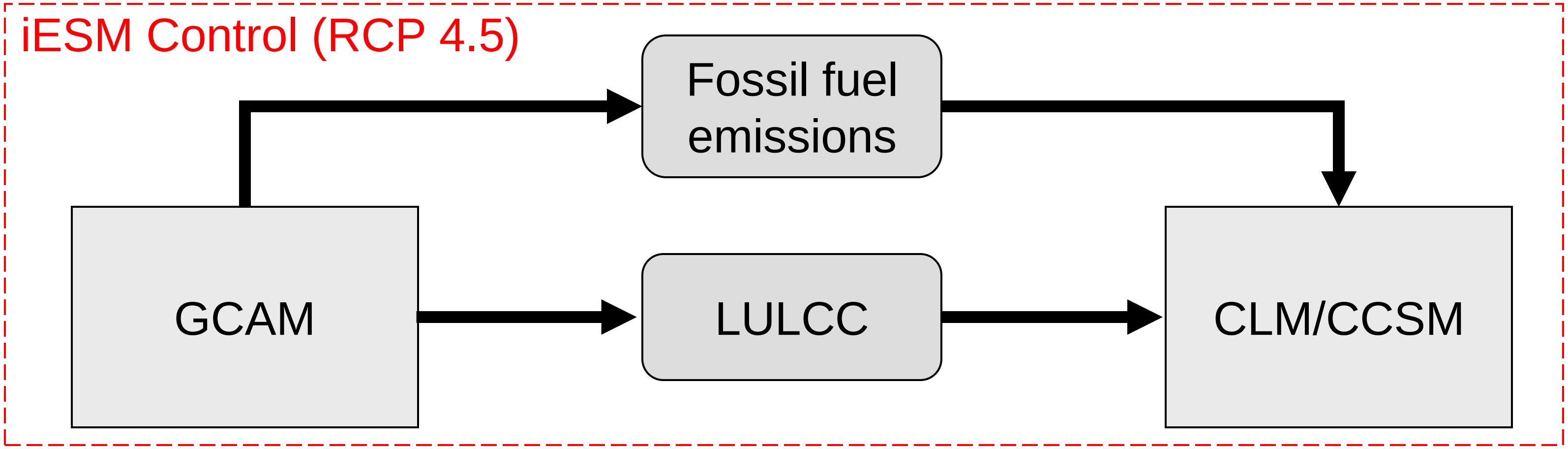
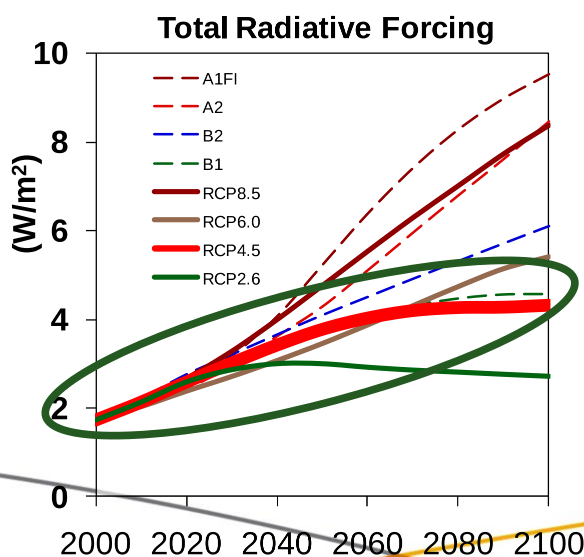
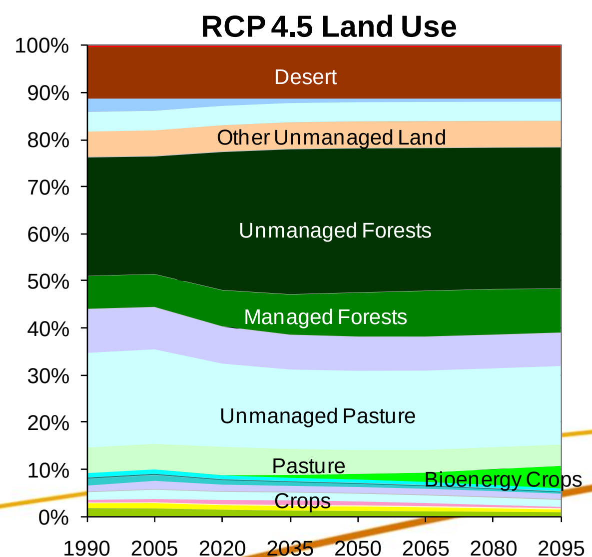
iESM Phase 1 Initial Coupling Strategy







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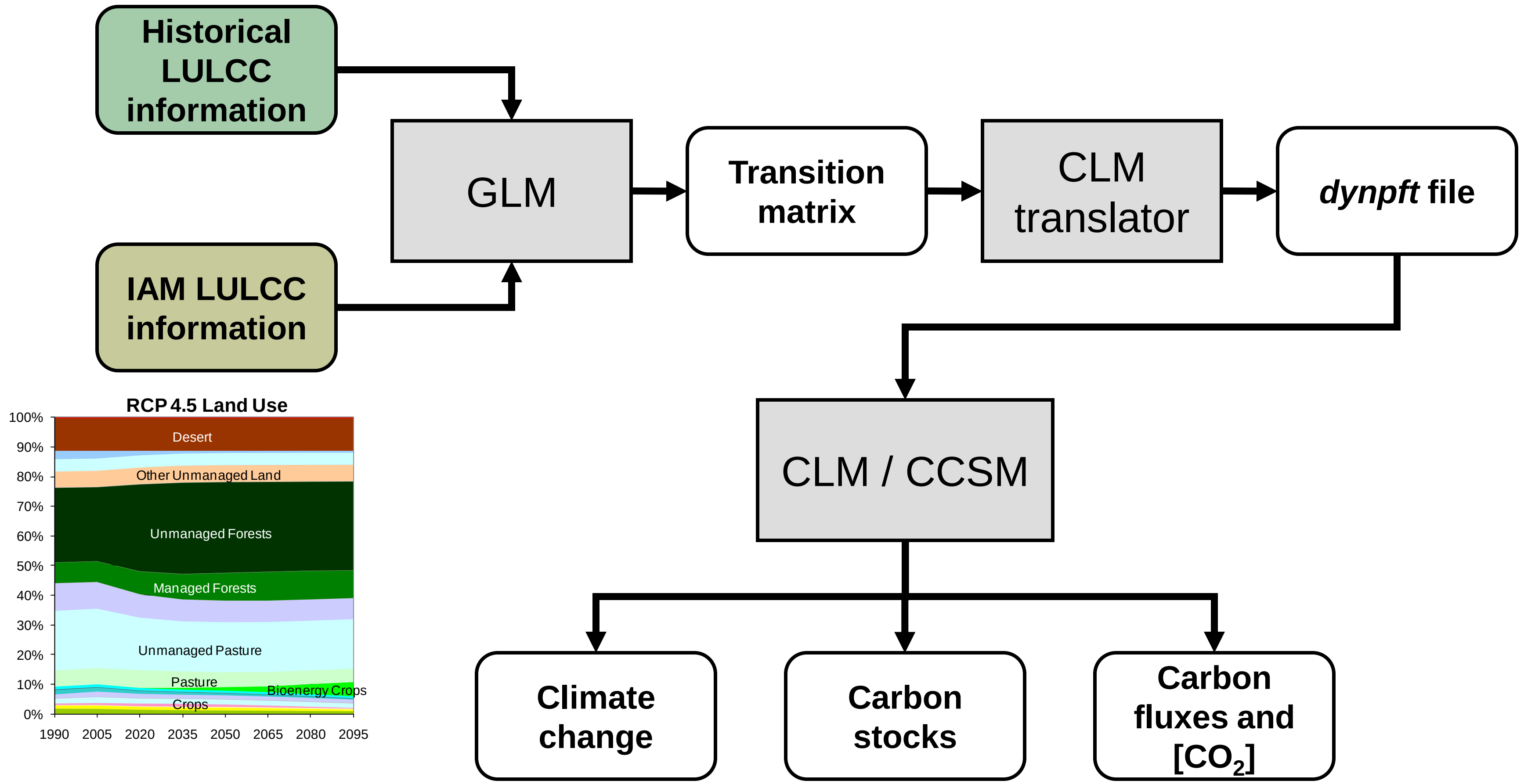
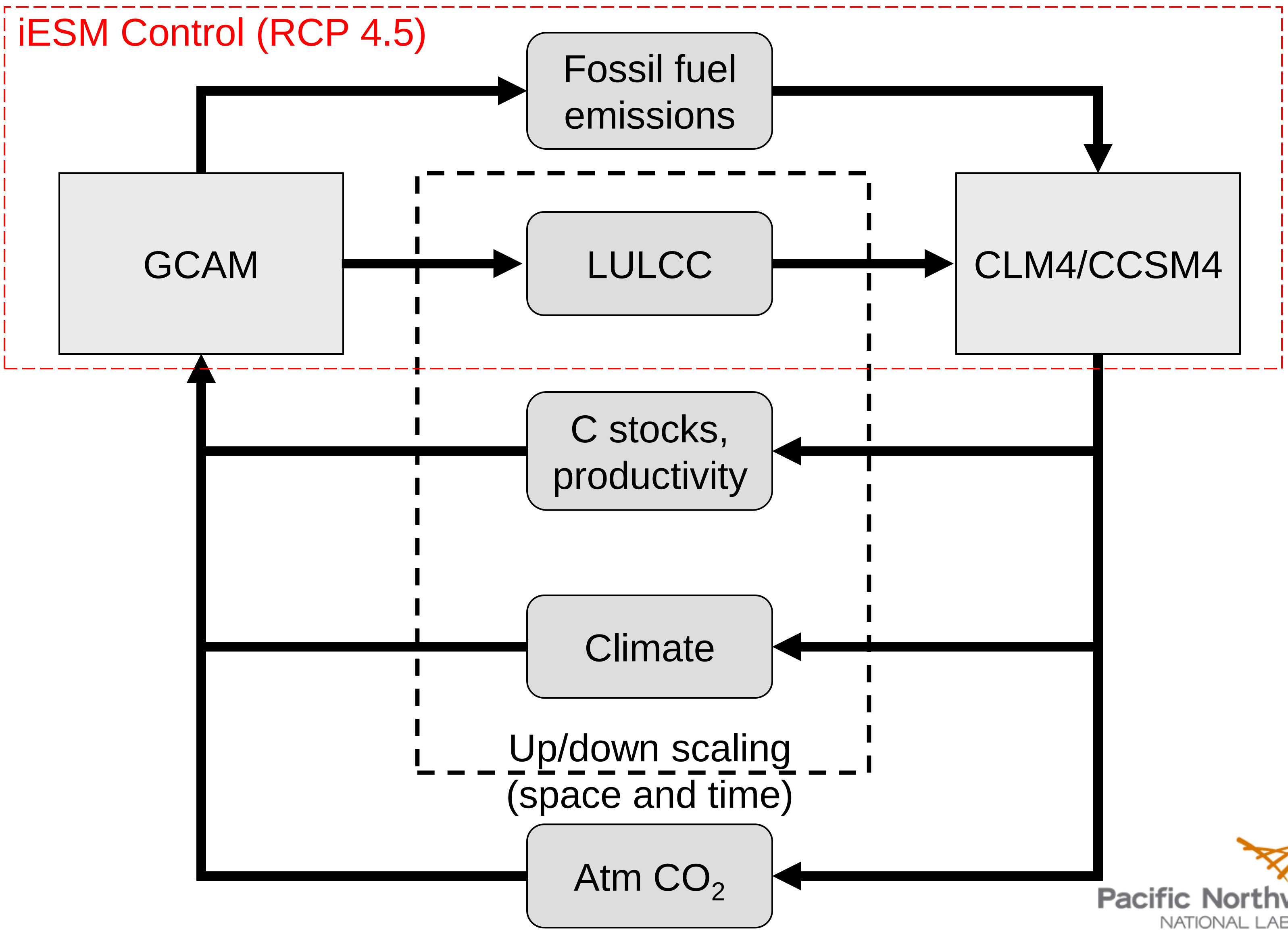
THE CLM: Initial One-way Coupling: Land Use and Land Cover Change (iESM Control experiment)



iESM multi-phase coupling strategy



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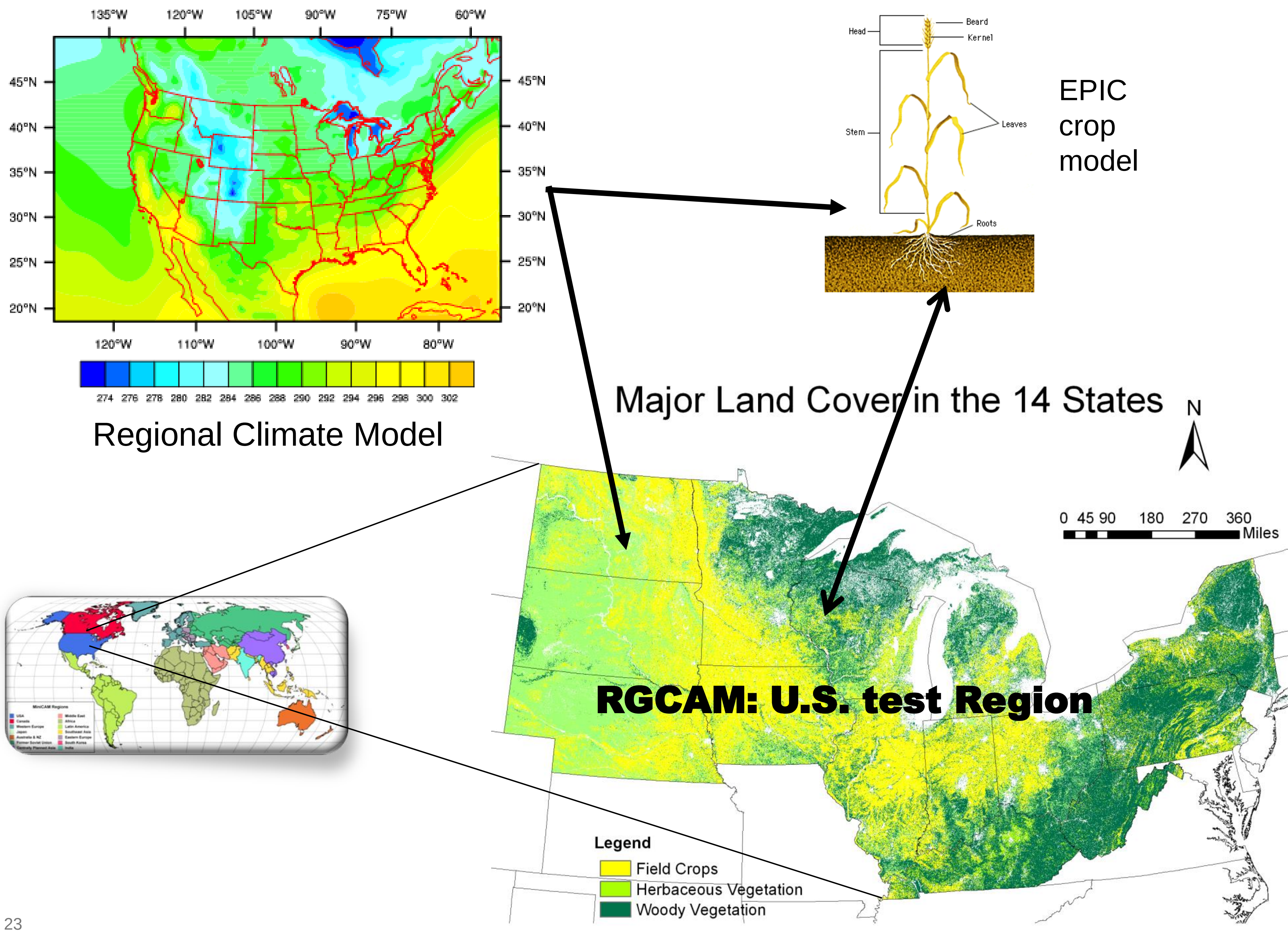
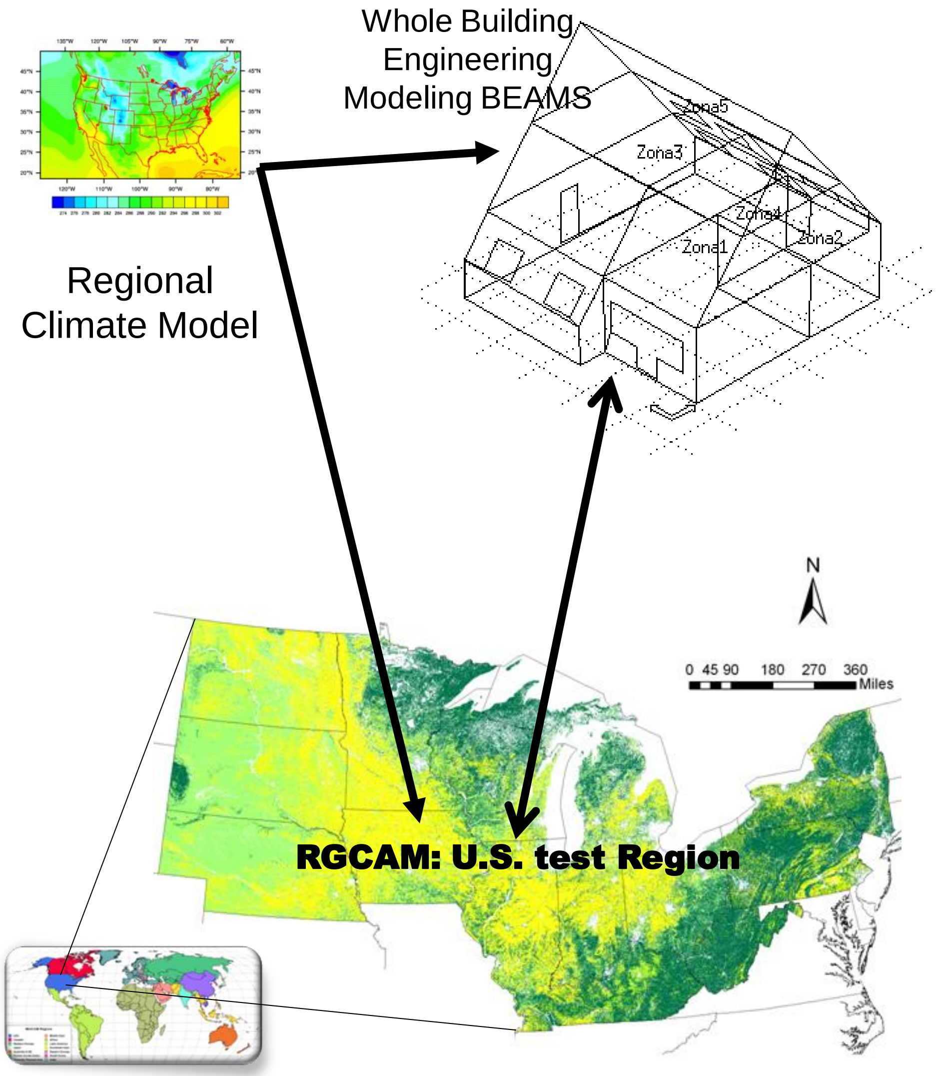
Examples of Linkages between Platforms: Regional Initiative



135°W
120°W
105°W
90°W
75°W
60°W
45°N
40°N
35°N
30°N
25°N
20°N
120°W
110°W
100°W
90°W
80°W
274 276 278 280 282 284 286 288 290 292 294 296 298 300 302
Regional Climate Model
Head
Beard
Kernel
Stem
Leaves
Roots
EPIC crop model
Major Land Cover in the 14 States
N
0 45 90 180 270 360
Miles
RGCAM: U.S. test Region
Legend
Field Crops
Herbaceous Vegetation
Woody Vegetation

Buildings Demand Modeling



BEND Model

- ~4000 buildings will be simulated in EnergyPlus to represent the buildings in the RGCAM U.S. test region:
  - 4 climate zones
  - 11 commercial building types
  - 3 residential building types
  - 6-9 sizes within each building type
  - 7-8 vintages of existing buildings and 3 vintages of new buildings
- Building characteristic vary for each combination of attributes
- Hourly (8760 hours) electrical output used to calibrate models and determine building weights based on actual weather and actual hourly electric consumption for test region.
- Our challenge is to pass data back and forth between BEAMS and R-GCAM.

Discussion

Evergreen

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Climate Damages in the MIT IGSM

John Reilly

MIT Joint Program on the Science and Policy of Global Change

Integrated assessment models (IAMs) have proven useful for analysis of climate change because they represent the entire inhabited earth system, albeit typically with simplified model components that are reduced form or more highly aggregated than for example, high resolution coupled atmosphere-ocean-land general circulation models. The MIT Integrated Global System Model has been developed to retain the flexibility to assemble earth system models of variable resolution and complexity, however, even at its simplest it remains considerably more complex than most other IAMs. In its simplest formulation it retains a full coupled general circulation model of the ocean and atmosphere. Solved recursively, it solution time for a 100-year integration on a single node of computer cluster is on the order of 24-36 hours, compared with seconds or minutes for other IAMs. In that form it is not numerical feasible to solve the whole system as a fully dynamic optimizing model to find an optimal cost-benefit solution as with the DICE, PAGE, or FUND models. Indeed, inclusion of climate damages is still a work in progress in the MIT IGSM. The slow progress relative to other efforts stems from a commitment to represent explicitly the physical impacts of climate and environmental change on activities (e.g. crop yields, water availability, coastal, inundation, ecosystem processes and functioning, health outcomes, etc.) and represent market response to these outcomes and value that response consistent with projections of resource prices as they are projected to change in the future with economic growth and under different policies to mitigate greenhouse gas emissions. This is in contrast to most of the optimizing models where climate damages are estimated as a reduced form relationship in dollars of economic loss as a function of mean global temperature change as a sufficient indicator of many dimensions of climate change, and where the damage function is itself completely independent and separable from the economy as it affects energy use and greenhouse gas emissions. In the "horses for courses" metaphor, the MIT IGSM is not a horse designed (bred) to run well if the course is to estimate a net present value social cost of carbon. The IGSM is best seen as complementary to such efforts, and probably the focus on uncertainty in future climate outcomes is one of the areas where it can make the most contribution to the social cost of carbon discussion.

Computationally efficient versions of the IGSM have been assembled for simulating large ensembles to study uncertainty (***Sokolov et al.,* 2009*;* *Webster et al.,* 2009**). Less complete but more highly-resolved model components can be combined where research demands them, such as in the study of the climate effect of aerosols (***Wang,* 2009*;* *Wang et al.,* 2009*a,b***), changes in atmospheric composition and human health (***Selin et al.,* 2009a**) or agricultural impacts and land use change (**Reilly, et al. 2007; Felzer et al., 2005; *Melillo et al.,* 2009**). The IGSM framework encompasses the following components:

- global economic activity resolved for large countries and regions that projects changes in human activities as they effect the earth system including emissions of pollutants and radiatively active substances and changes in land use and land cover;

- earth system modules linked to the macroeconomy that address effects of climate and environmental change on human activity, adaptation, and their consequences for the macroeconomy (this includes modules that represent water use and land use at disaggregated spatial scales, energy and coastal infrastructure again at disaggregate spatial scales, and demography, urbanization, urban air chemistry, and epidemiological relationships that relate environmental change to human health);
- the natural and managed land system including vegetation, hydrology, and biogeochemistry as affected by human activity, environmental change and feedbacks on climate and atmospheric composition;
- the circulation and biogeochemistry of the ocean including its interactions with the atmosphere, and representations of physical and biological oceanic responses to climate change; and
- the circulation and chemistry of the atmosphere including its role in radiative forcing, and interactions with the land and ocean that determine climate change.

The suite of models that have been employed in this framework and their capabilities are briefly described below.

3.1 Human Drivers and Analysis of Impacts

Human activities as they contribute to environmental change or are affected by it are represented in multi-region, multi-sector models of the economy that solves for the prices and quantities of interacting domestic and international markets for energy and non-energy goods as well as for equilibrium in factor markets. The MIT Emissions Predictions and Policy Analysis (EPPA) model (***Paltsev et al.,*** **2005**) covers the world economy. It is built on the GTAP dataset (maintained at Purdue University) of the world economic activity augmented by data on the emissions of greenhouse gases, aerosols and other relevant species, and details of selected economic sectors. The GTAP database allows flexibility to represent the world economy with greater country or sector detail (the data set has 112 countries/regions and 57 economic sectors) that we aggregate further for numerical efficiency. The model projects economic variables (GDP, energy use, sectoral output, consumption, *etc*.) and emissions of greenhouse gases (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6) and other air pollutants (CO, VOC, NO_x, SO_2, NH_3, black carbon, and organic carbon) from combustion of carbon-based fuels, industrial processes, waste handling, and agricultural activities.

The model has been augmented with supplemental physical accounts to link it with the earth system components of the IGSM framework. To explore land use and environmental consequences, the EPPA model (***Gurgel, et al.,*** **2007**; ***Antoine, et al.***,**2008**) is coupled with the Terrestrial Ecosystem Model (***Melillo et al.,*** **2009**). The linkage allows us to examine the ability of terrestrial ecosystems to supply biofuels to meet growing demand for low-emissions energy sources along with the growing demand for food, and to assess direct and indirect emissions from an expanded cellulosic bioenergy program. The approach generates worldwide land-use scenarios at a spatial resolution of 0.5º latitude by 0.5º longitude that varies with climate change. To analyze the economic impacts of air pollution, the EPPA model is extended to include pollution-generated health costs, which reduce the resources available to the rest of the economy (***Nam et al.,*** **2009*; Selin et al.,*** **2009a**). The model captures the amount of labor and leisure lost and additional medical services required due to acute and chronic exposure to pollutants. The GTAP database allows considerable flexibility to represent the world economy with greater country or sector detail (the underlying data has 112 countries/regions and 57 economic sectors). To assess distributional and regional impacts of carbon policy in the US, we use a model that is based on a state-level database and resolves large U.S. states and multi-state regions and households of several income classes. The U.S. Regional Energy Policy (USREP) model (***Rausch et al.,*** **2009; 2010**) is nearly identical in structure to the EPPA model, except that it models states and multi-state regions in the US instead of countries and multi-country regions. The main difference from the EPPA model is the foreign sector that is represented as export supply and import demand functions rather than a full representation of foreign economies. This sacrifice of global coverage allows explicit modeling of distributional details of climate legislation and linking the USREP model to very detailed electricity dispatch models. Efforts, under separate funding, to integrate the USREP database into the GTAP base to provide a complete representation of trade are underway. Physical impacts of environmental change have been included in the model as a feedback by identifying factors (land productivity as it affects crops, livestock and forests) or sectors affected by climate or by introducing additional household production sectors (household health services that uses leisure and medical services). Thus, the approach is to work with underlying input-output and Social Accounting Matrix (SAM) that is the basis for the economic model (***Matus, et al.,*** **2008**). This provides a framework for potentially linking other impacts such as coastal (***Franck et al.,*** **2010a,b, 2010;** ***Sugiyama, et al.***, **2008**), agriculture (Reilly et al., 2007), health (***Selin, et al***., **2009;** ***Nam et al***., **2010**), or water (***Strzepek et al.,*** **2010**) impacts.

3.2 Hydrology and Water Management

Research on components representing water management are aimed at linking hydrological changes projected by the atmospheric component of the IGSM to impacts of those changes on water availability and use for irrigation, energy, industry and households, and in-stream ecological services. These demands are driven by macroeconomic changes and changes in water supply and will in turn affect the economy as represented in the EPPA and the USREP models. Techniques have been developed to take IGSM 2-D GCM outputs and use results from the IPCC AR-4 3-D GCMs to provide IGSM-generated 3-D climates to the hydrology component of the IGSM-Land Surface Model (NCAR Community Land Model, CLM) to project runoff. Tests have been conducted for the US, where adequate data are available, to determine the spatial resolution needed to provide reliable estimates of runoff using CLM. A Water Resources System (WRS) model has been adapted from and further developed in collaboration with the International Food Policy Research Institute (IFPRI) to represent river reaches and natural and management components that affect stream-flow. The major natural components are wetlands, unmanaged lakes, groundwater aquifers and flood plains. The major managed components are reservoirs and managed lakes, and water diversions for irrigation, cooling in thermal power plants, and industrial and household needs. Constraints on use to preserve in-stream ecological water requirements can be imposed.

A series of models were adapted and developed to represent water use. These include a crop growth model (CLICROP) developed to be able to run at 2° latitude-longitude grid resolution while retaining the accuracy of a 0.5° resolution, thereby improving numerical efficiency of the modeling system (***Strzepek***

et al.,* 2010a**). A model of Municipal and Industrial water demand driven by per capita GDP was developed jointly with the University of Edinbourgh (*Hughes et al.,* 2010; ***Strzepek et al.,* 2010a**). To investigate changes in thermal electric cooling water demands, a geospatial methodology based on energy generation and geo-hydroclimatic variables has been developed (Strzepek et al.,* 2010b**). An assessment of environmental flow requirements to assure aquatic ecosystem viability has been undertaken and an approach for using the IGSM was selected (***Strzepek & Boehlert,* 2010; *Strzepek et al.,* 2010a**). These developments provide the foundation for completing linkages of the WRS with other IGSM components.

3.3 Atmospheric Dynamics and Physics

Research utilizing the IGSM framework has typically included a 2-D atmospheric (zonally-averaged statistical dynamical) component based on the Goddard Institute for Space Studies (GISS) GCM. The IGSM version 2.2 couples this atmosphere with a 2D ocean model (latitude, longitude) with treatment of heat and carbon flows into the deep ocean ***(Sokolov et al, 2005).*** The IGSM version 2.3 (where 2.3 indicates the 2-D atmosphere/full 3-D ocean GCM configuration) (***Sokolov et al.,* 2005**; ***Dutkiewicz et al.,* 2005**) is a fully-coupled Earth system model that allows simulation of critical feedbacks among its various components, including the atmosphere, ocean, land, urban processes and human activities. A limitation of the IGSM2.3 is the above 2-D (zonally averaged) atmosphere model that does not permit direct regional climate studies. For investigations requiring 3-D atmospheric capabilities, the National Center for Atmospheric Research (NCAR) Community Atmosphere Model version 3 (CAM3) (***Collins et al.,*** 2006) has been used with offline coupling.

The IGSM2.3 provides an efficient tool for generating probabilistic distributions of sea surface temperature (SST) and sea ice cover (SIC) changes for the 21st century under varying emissions scenarios, climate sensitivities, aerosol forcing and ocean heat uptake rates. Even though the atmospheric component of the IGSM2.3 is zonally-averaged, it provides heat and fresh-water fluxes separately over the open ocean and over sea ice, as well as their derivatives with respect to surface temperature. This resolution allows the total heat and fresh-water fluxes for the IGSM2.3 oceanic component to vary by longitude as a function of SST so that, for example, warmer ocean locations undergo greater evaporation and receive less downward heat flux.

In offline coupling between the IGSM2.3 and CAM3, the 3-D atmosphere is driven by the IGSM2.3 SST anomalies with a climatological annual cycle taken from an observed dataset (*Hurrell et al.*, 2008), instead of the full IGSM2.3 SSTs, to provide a better SST annual cycle, and more realistic regional feedbacks between the ocean and atmospheric components. This approach yields a consistent regional distribution and climate change over the 20th century as compared to observational datasets, and can then be used for simulations of the 21st century.

3.4 Urban and Global Atmospheric Chemistry and Aerosols

The model of atmospheric chemistry includes an analysis of all the major climate-relevant reactive gases and aerosols at urban scales coupled to a model of the chemistry of species exported from urban/regional areas (plus the emissions from non-urban areas) at global scale. For calculation of the atmospheric composition in non-urban areas, the atmospheric dynamics and physics model is linked to a detailed 2-D zonal-mean model of atmospheric chemistry. The atmospheric chemical reactions are thus simulated in two separate modules: one for the sub-grid-scale urban chemistry and one for the 2-D model grid. In addition, offline studies also utilize the 3-D capabilities of the CAM3 as noted above, as well as the global Model of Atmospheric Transport and Chemistry (MATCH; *Rasch et al.,* 1997), and the GEOS-Chem global transport model (http://geos-chem.org/).

Global Atmospheric Chemistry: Modeling of atmospheric composition at global scale is by the above 2-D zonal-mean model with the continuity equations for trace constituents solved in mass conservative or flux form (**Wang *et al*.**, **1998**). The model includes 33 chemical species including black carbon aerosol, and organic carbon aerosol, and considers convergences due to transport, convection, atmospheric chemical reactions, and local production/loss due to surface emission/deposition. The scavenging of carbonaceous and sulfate aerosol species by precipitation is included using a method based on a detailed 3-D climate-aerosol-chemistry model (***Wang***, **2004**) that has been developed in collaboration with NCAR. The interactive aerosol-climate model is used offline to model distributions of key chemical species, such as those utilized in the development of the urban air chemistry model.

Urban Air Chemistry: A reduced-form urban chemical model that can be nested within coarser-scale models has been developed and implemented to better represent the sub-gridscale urban chemical processes that influence air chemistry and climate (***Cohen & Prinn***, **2009**). This is critical both for accurate representation of future climate trends and for our increasing focus on impacts, especially to human health and down-wind ecosystems. The MIT Urban Chemical Metamodel (UrbanM) is an update of our ***Mayer et al.*** **(2000)** model, and applies a third-order polynomial fit to the CAMx regional air quality model (*ENVIRON*, 2008) for 41 trace gases and aerosols for a 100 km x 100 km urban area. While a component of the IGSM, the urban modular UrbanM is also designed to facilitate inclusion in a number of other global atmospheric models. It has recently been embedded in the MIT interactive climate-aerosol simulation based on CAM3 in order to assess its influence on the concentration and distribution of aerosols in Asia (***Cohen et al.*****,** **2009**). Work is underway to further test the sensitivity of the probabilistic uncertainty results with the IGSM2.2/2.3 to this improved representation of urban chemistry. The UrbanM is presently being benchmarked in a case study of the Northeast U.S., and embedded in a global 3-D chemistry-climate model including a detailed chemical mechanism (NCAR CAM-Chem).

Chemistry-Climate-Aerosol Component: A 3-D interactive aerosol-climate model has been developed at MIT in collaboration with NCAR based on the finite volume version of the Community Climate System Model (CCSM3; *Collins et al.,* 2006). Focused on analysis of aerosols, this companion sub-model is not yet integrated into the IGSM but serves as a step toward overcoming the limitations for analysis of regional issues using the IGSM 2-D atmosphere configuration. The modeled aerosols include three types of sulfate, two external mixtures of black carbon (BC), one type of organic carbon, and one mixed state (comprised primarily of sulfate and other compounds coated on BC); each aerosol type has a prognostic size distribution (***Kim et al***., **2008**). The model incorporates such processes as aerosol nucleation, diffusive growth, coagulation, nucleation and impaction scavenging, dry deposition, and wet removal. It has been used to investigate the global aerosol solar absorption rates (***Wang et al.,*** **2009a**) and the impact of absorbing aerosols on the Indian summer monsoon (***Wang et al.,* 2009b**). The UrbanM has recently been introduced into this model to study the roles of urban processing in global aerosol microphysics and chemistry and to compute the abundance and radiative forcing of anthropogenic aerosols (***Cohen et al.,* 2010**). This effort also serves as the first step toward introducing the full UrbanM into the 3-D aerosol-chemistry-climate framework.

3.5 Ocean Component

The IGSM framework retains the capability to represent ocean physics and biogeochemistry in several different ways depending on the question to be addressed. It can utilize either the 2-D (latitude-longitude) mixed-layer anomaly-diffusing ocean model or the fully 3-D ocean general circulation model (GCM). The IGSM with the 2-D ocean is more computationally efficient and more flexible for studies of uncertainty in climate response. In applications that need to account for atmosphere-ocean circulation interactions, or for more detailed studies involving ocean biogeochemistry, the diffusive ocean model is replaced by the fully 3D ocean GCM component.

2-D Ocean Model: The IGSM2.2 has a mixed-layer anomaly-diffusing ocean model with a horizontal resolution of 4º in latitude and 5º in longitude. Mixed-layer depth is prescribed based on observations as a function of time and location. Vertical diffusion of anomalies into the deep ocean utilizes a diffusion coefficient that varies zonally as well as meridionally. The model includes specified vertically-integrated horizontal heat transport by the deep oceans, and allows zonal as well as meridional transport. A thermodynamic ice module has two layers and computes the percentage of area covered by ice and ice thickness, and a diffusive ocean carbon module is included (***Sokolov et al, 2005; Holian et al*., 2001; *Follows et al*. 2006**).

3-D Ocean General Circulation Model: The IGSM2.3 ocean component is based on a state-of-the-art 3D MIT ocean GCM (*Marshall et al.*, 1997). Embedded in the ocean model is a thermodynamic sea-ice module (***Dutkiewicz et al.,* 2005**). The 3D ocean component is currently configured in either a coarse resolution (4° by 4° horizontal, 15 layers in the vertical) or higher resolution (2° by 2.5°, 23 layers; or alternate configuration with higher resolution in the topics) depending on the focus of study and the computational resources available. The efficiency of ocean heat uptake can be varied (e.g., ***Dalan et al.* 2005**) and the coupling of heat, moisture, and momentum can be modified for process studies (e.g., ***Klima 2008***). In addition, a biogeochemical component with explicit representation of the cycling of carbon, phosphorus and alkalinity can be incorporated. Export of organic and particulate inorganic carbon from surface waters is parameterized and biological productivity is modelled as a function of available nutrients and light (***Dutkiewicz et al*., 2005)**. Air-sea exchange of CO_2 allows feedback between the ocean and atmosphere components. An additional module with explicit representation of the marine ecosystem (***Follows et al*., 2007**) has been introduced in an “offline” (i.e. without full feedbacks to the full IGSM) configuration (see further discussion in Section 4.2.3).

3.6 Land and Vegetation Processes

The Global Land System (GLS, ***Schlosser et al*., 2007**) of the IGSM links biogeophysical, ecological, and biogeochemical components: (1) the NCAR Community Land Model (CLM), which calculates the global, terrestrial water and energy balances; (2) the Terrestrial Ecosystems Model (TEM) of the Marine Biological Laboratory, which simulates carbon (CO_2) fluxes and the storage of carbon and nitrogen in vegetation and soils including net primary production and carbon sequestration or loss; and (3) the Natural Emissions Model (NEM), which simulates fluxes of CH_4 and N_2O, and is now embedded within TEM. A recent augmentation to the GLS enables a more explicit treatment of agricultural processes and a treatment of the managed water systems (***Strzepek et al*., 2010a**). The linkage between econometrically based decisions regarding land use (from EPPA) and plant productivity from TEM has been enhanced (***Cai et al*., 2010**). And the treatment of migration of plant species to include meteorological constraints (i.e. winds) to seed dispersal has been enhanced (***Lee et al***., **2009, 2010a,b**). The representation of natural and vegetation processes also includes a diagnosis of the expansion of lakes and changes of methane emissions from thermokarst lake expansion/degradation (***Gao et al*., 2010**; ***Schlosser et al*., 2010**). In addition, continuing updates to CLM and TEM are also incorporated into the GLS framework. In all these applications, the GLS is operating under a range of spatial resolutions (from zonal to gridded as low as 0.5º), and is configured in its structural detail to accommodate various levels of process-oriented research both in a coupled framework within the IGSM as well as in standalone studies (i.e. with prescribed atmospheric forcing).

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Land Use In the MIT IGSM: The Role of Biofuels and Forests in Mitigating Climate Risks

John Reilly

Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology

5 November 2010, Purdue

Economic Models of Land Use and Biofuels

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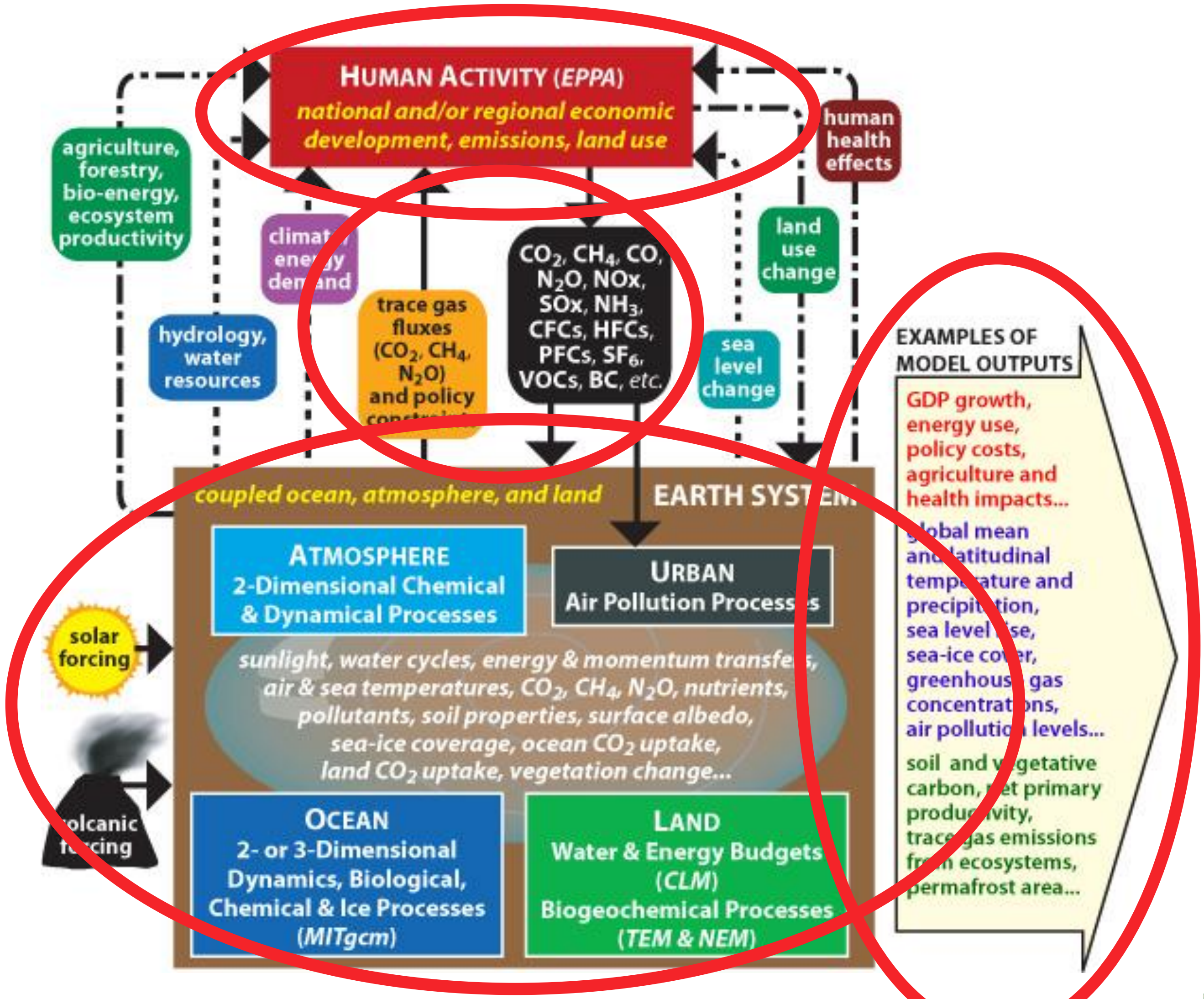
MIT INTEGRATED GLOBAL SYSTEM MODEL



Global Land System Interactions

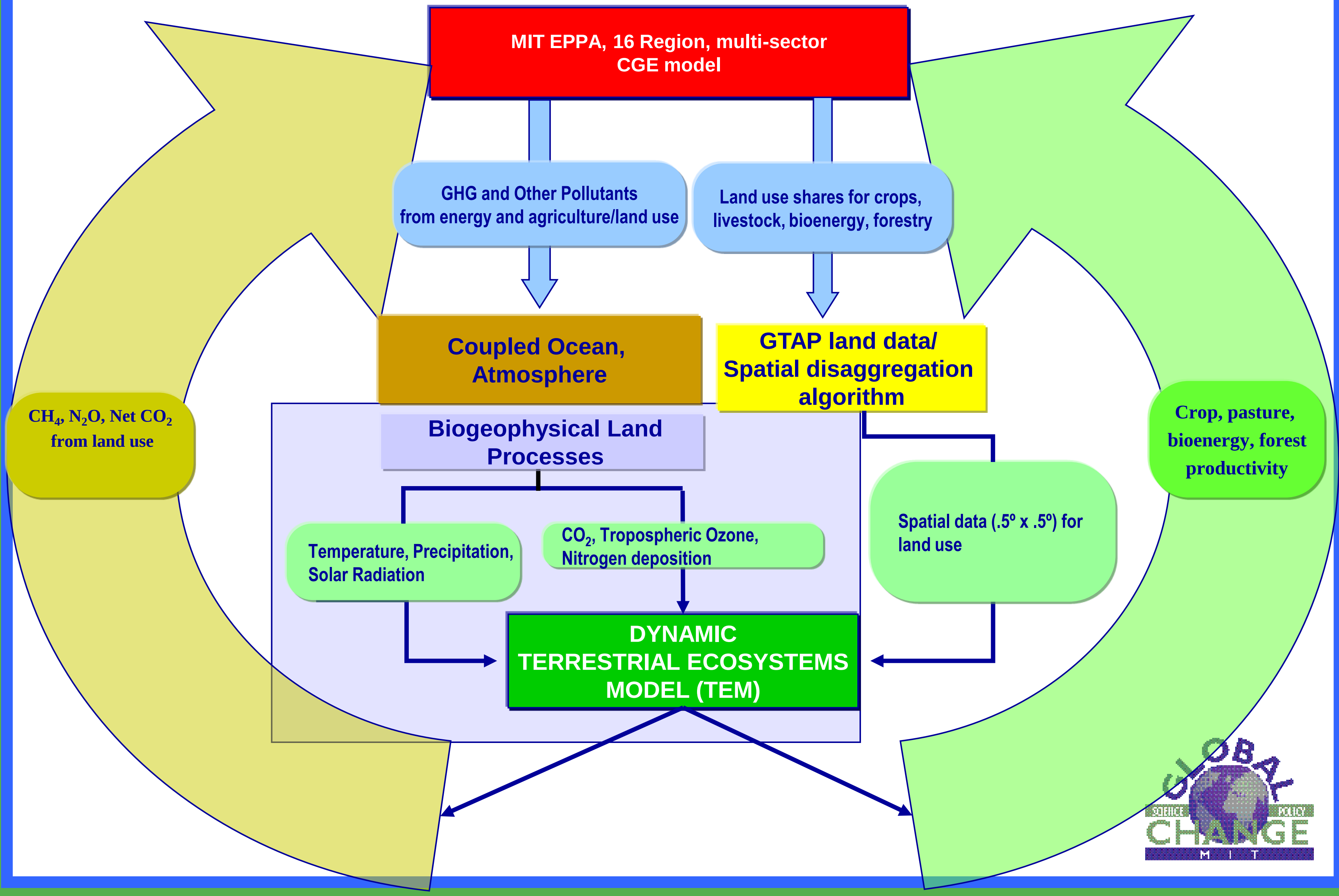


Table 1. Regions, Sectors, and Primary Factors in the EPPA Model

Country or Region	Sectors	Factors
Developed	*Non-Energy*	Capital
United States (USA)	Services (SERV)	Labor
Canada (CAN)	Energy-Intensive (EINT)	*Energy Resources*
Japan (JPN)	Other Industries (OTHR)	Crude Oil
European Union+ (EUR)	Commercial Transp. (TRAN)	Natural Gas
Australia/N.Zealand (ANZ)	Household Transp. (HTRN)	Coal
Former Soviet Union (FSU)	***Other HH Consumption - Recreation***	Oil Shale
Eastern Europe (EET)	**Hunting and Fishing (REHF)**	Nuclear
Developing	**Wildlife Viewing in Reserves (REWV_R)**	Hydro
India (IND)	**Other Wildlife Viewing (REWV_N)**	Wind/Solar
China (CHN)	*Fuels*	*Land*
Indonesia (IDZ)	Coal (COAL)	Cropland
Higher Inc. East Asia (ASI)	Crude Oil (OIL)	Pastureland
Mexico (MEX)	Refined Oil (ROIL)	Managed Forest
Centr. & S. America (LAM)	Natural Gas (GAS)	**Non-Reserved**
Middle East (MES)	Oil from Shale (SYNO)	**Natural Forest**
Africa (AFR)	Synthetic Gas (SYNG)	**Reserved Natural**
Rest of World (ROW)	Liquids from Biomass (B-OIL)	**Forest**
	Electricity Generation	Natural Grassland
	Fossil (ELEC)	Other
	Hydro (HYDR)	
	Nuclear (NUCL)	
	Solar and Wind (SOLW)	
	Biomass (BIOM)	
	Coal with CCS (IGCAP)	
	Adv. gas without CCS (NGCC)	
	Gas with CCS (NGCAP)	
	Agriculture	
	Crops (CROP)	
	Livestock (LIVE)	
	Forest products (FORS)	
	Food Processing (FOOD)	

Expanded SAM—Household "production" sector, leisure

		INTERMEDIATE USE by Production Sectors				*Household Services*		FINAL USE				OUT-
		1	2	...j...	n	**hh Prod.**	***Labor-Leisure Choice***	Private consum.	Gov't consum.	Invest.	Export	PUT
Domestic Production	1											
	2											
	:											
	i			A					B			C
	n											
Imports	1											
	2											
	:											
	i			D					E			F
	:											
	n											
Leisure							***Leisure***	***Leisure***				
Value added:	-labor					***Labor***	***Labor***	***Labor***				
	-capital			G					H			I
	- natural resources											
INPUT				J								

Biofuels
Bioelec
Crops
Livestock
forestry

Environmental health provision

recreation

Unmanaged land, recreation future value

Land for crops, pasture, forestry — productivity affected by environmental change.

Added components are in bold italic.

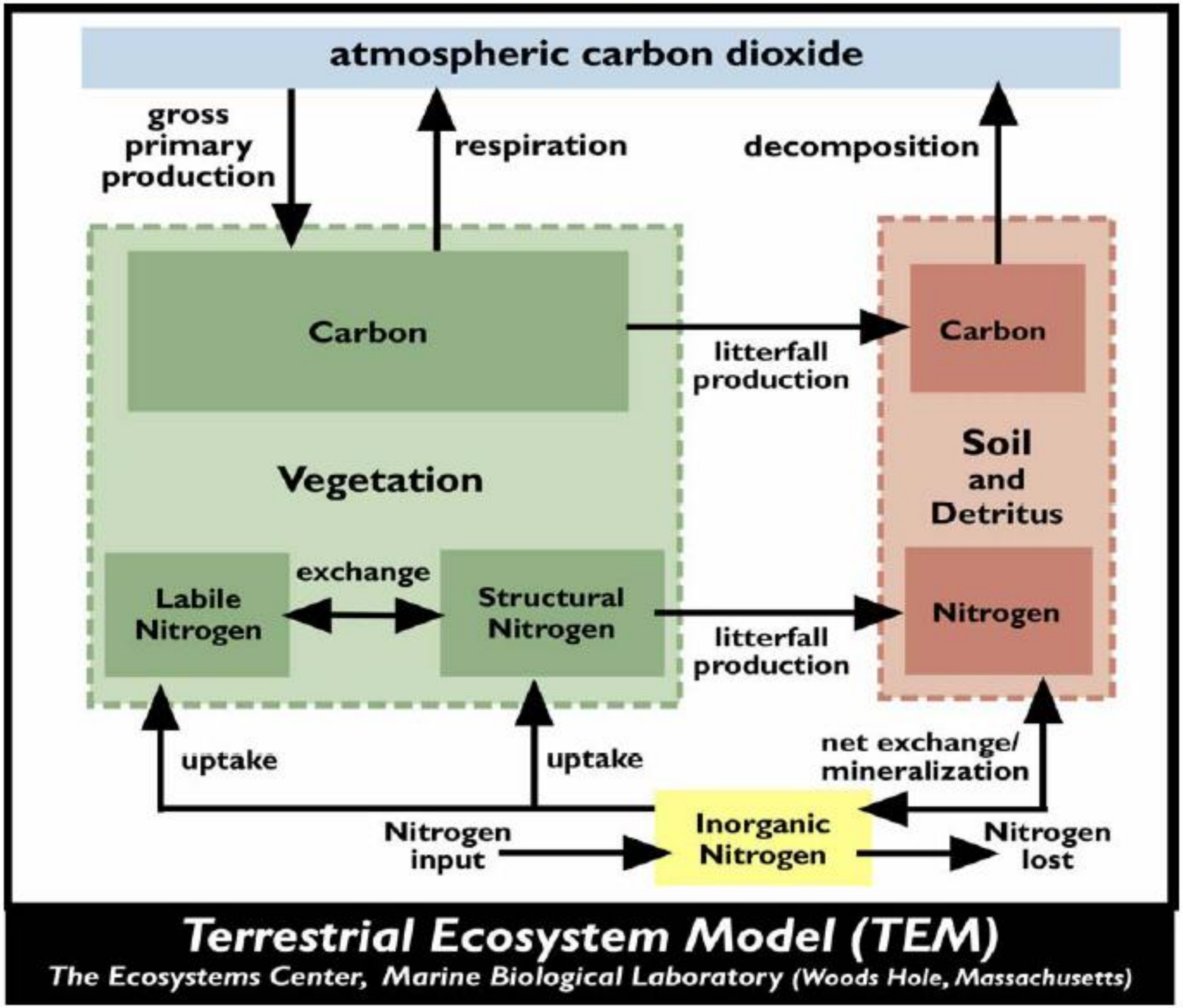


Figure 3.4: Description of the Terrestrial Ecosystem Model (TEM)
Source: The Ecosystems Center, the U.S. Marine Biological Laboratory (MBL).

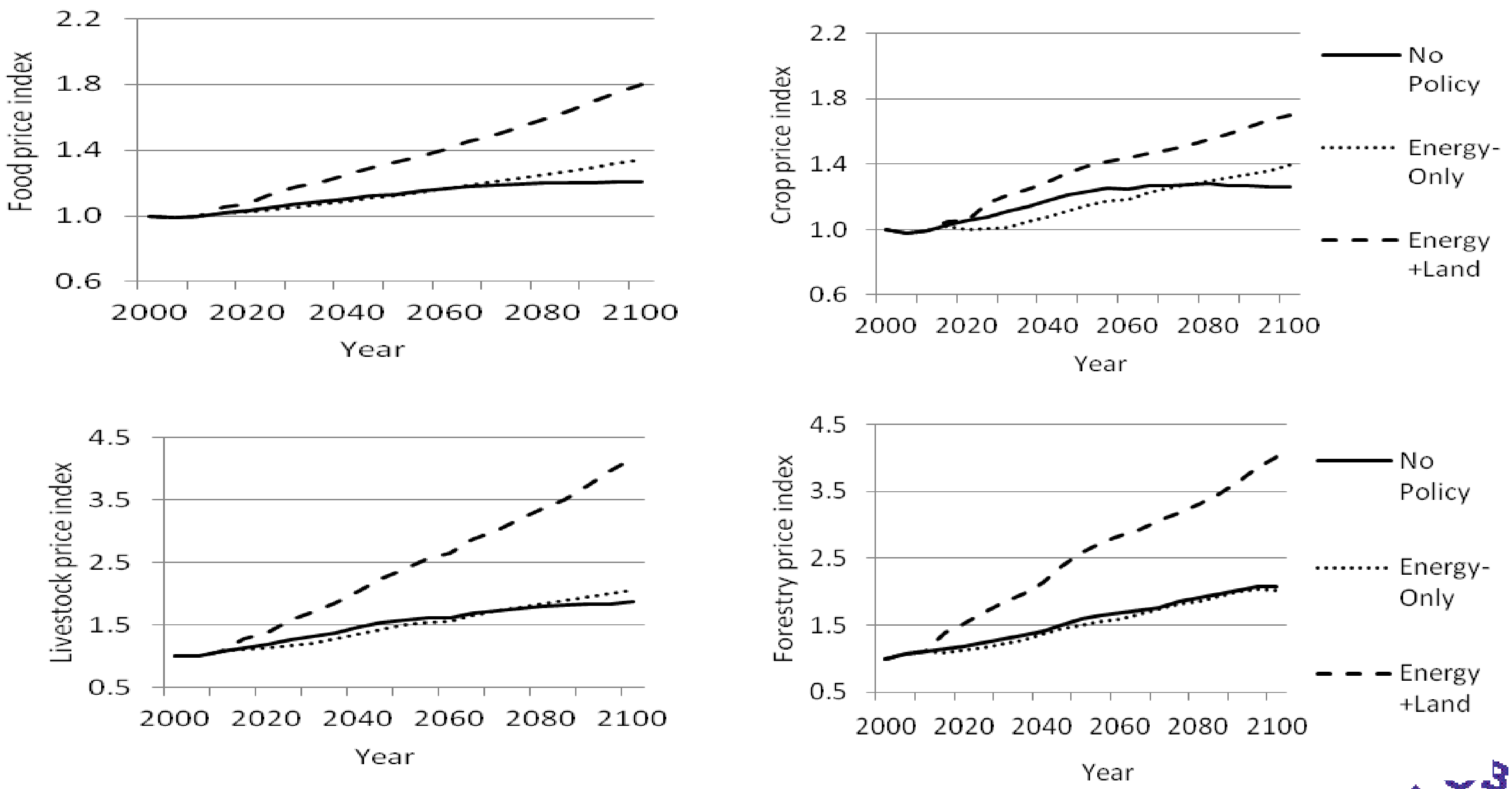
Monthly,

0.5° x 0.5°,

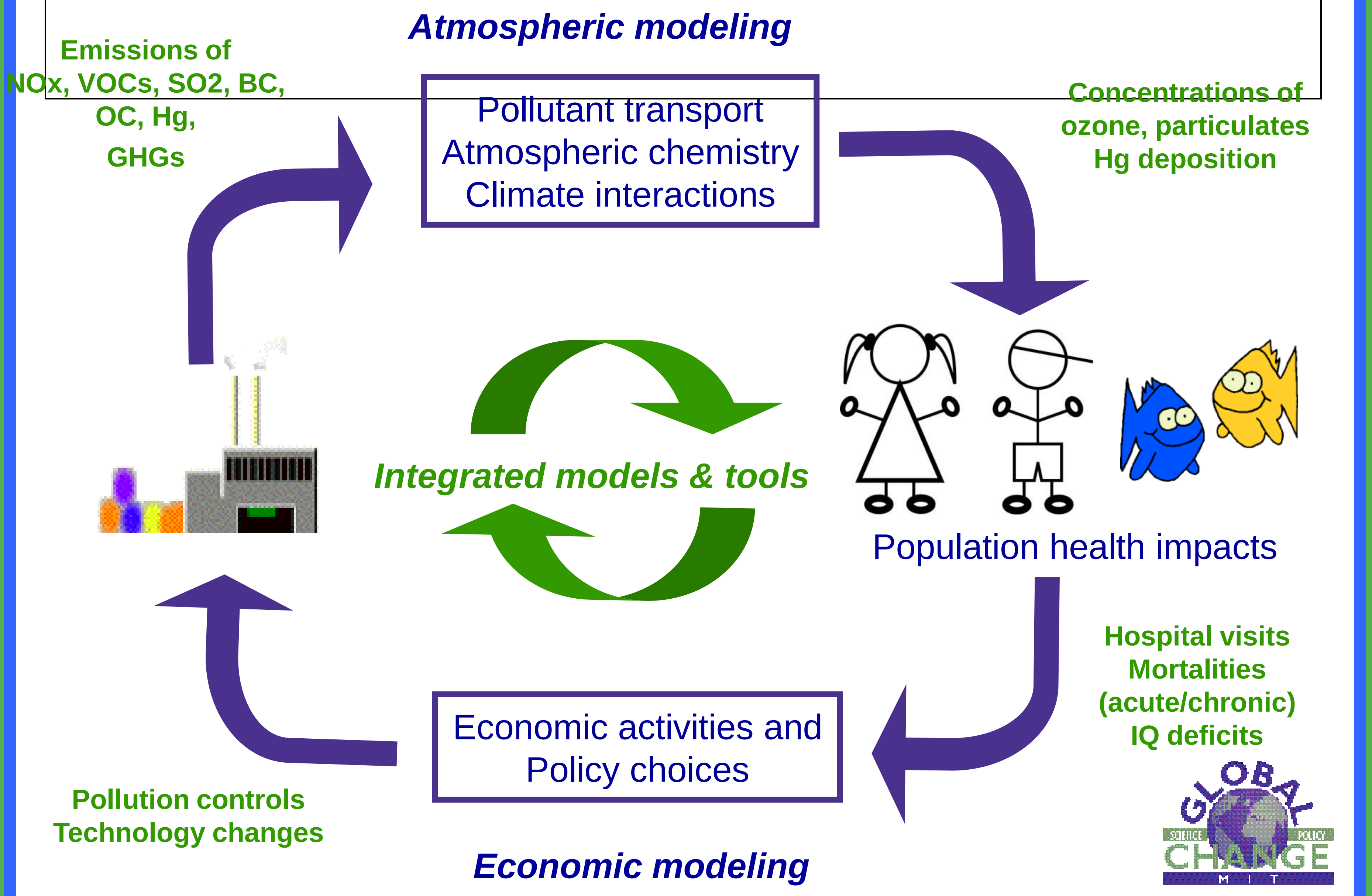
Dynamic soils and vegetation with multiple carbon pools, and multiple harvest carbon pools i.e. forest litter, waste, paper; lumber

GLOBAL SCIENCE POLICY CHANGE MIT

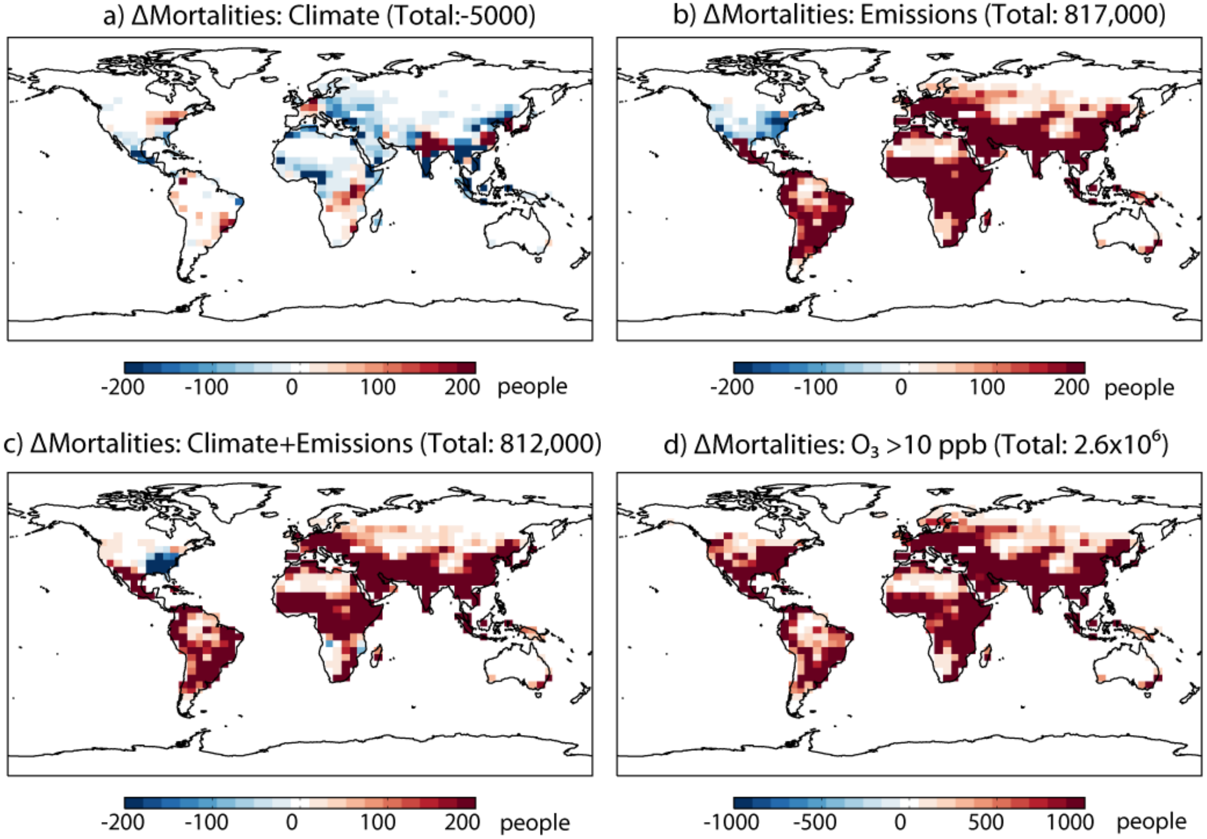
Food, crop, livestock, and forestry price impacts combine impacts of climate change, ozone, competition for land of biofuels, and mitigation cost effects on energy/N_2O/CH_4



FRAMEWORK FOR AIR POLLUTION IMPACTS ANALYSIS



GLOBAL COSTS OF OZONE POLLUTION IN 2050

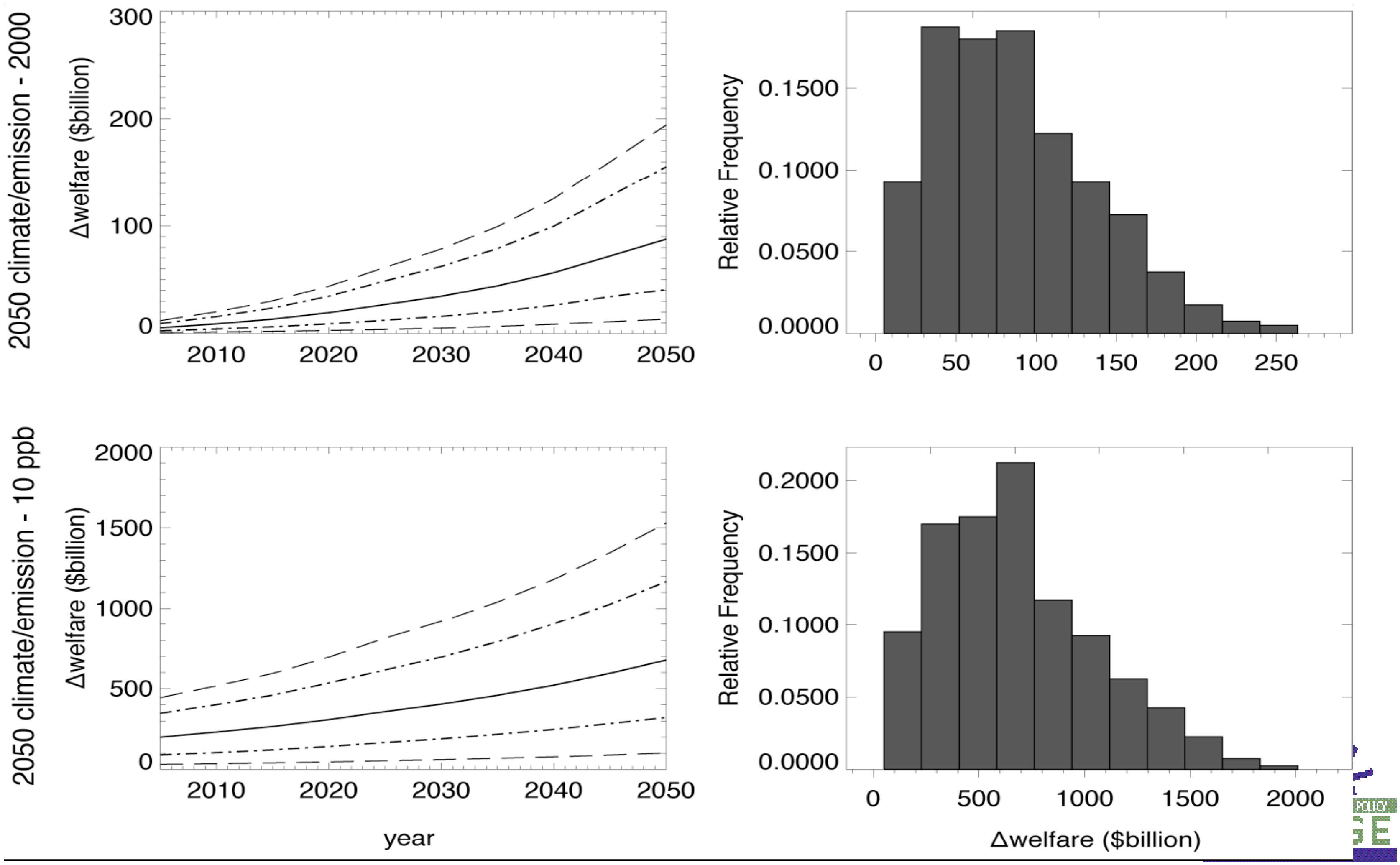


- O_3 from A1B scenario [Wu et al., 2008] to 2050
- Calculate change in welfare due to health impacts of ozone changes, separately for emissions and climate drivers

- 2050 welfare loss from O_3 health impacts, climate only scenario: *€790 million* (year 2000 €)
- 2050 welfare loss from climate+emission changes: *€120 billion*
- 2050 welfare loss from all O_3 above background: *€580 billion*

[*Selin et al.*, in prep]

Uncertainty: Due to uncertainty in dose response relationships and economic modeling of impacts.



Uncertainty Analysis: Methodology

Estimate probability distributions for input parameters controlling the emissions and climate projections in IGSM sub-models:

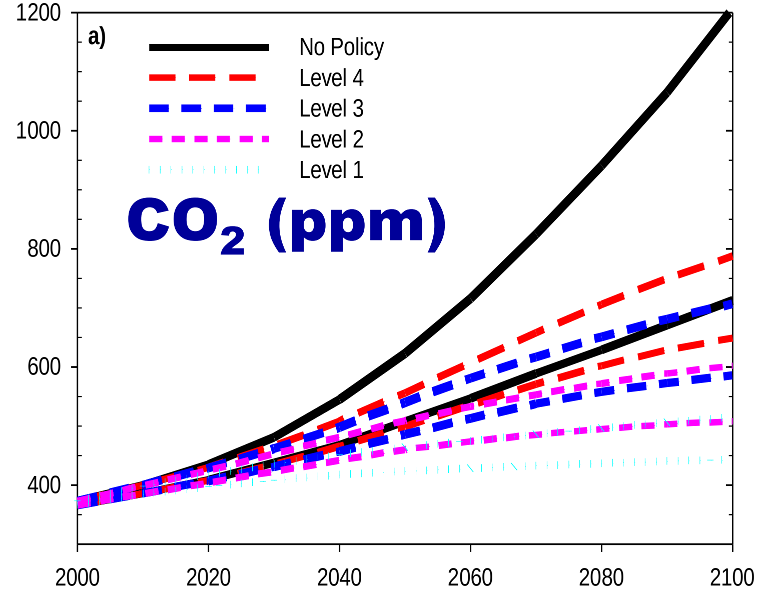
(1) Emissions Uncertainties:
Elasticities of Substitution
GDP Growth (based on Labor Productivity Growth)
Autonomous Energy Efficiency Improvement (AEEI)
Fossil Fuel Resource Availability, Population Growth
Urban Pollutant Trends, Future Energy Technologies
Non-CO_2 Greenhouse Gas Trends, Capital Vintaging
(2) Climate System Response Uncertainties (constrained by observations):
Climate Sensitivity
Rate of Heat uptake by Deep Ocean
Radiative Forcing Strength of Aerosols
(3) Greenhouse Gas Cycle Uncertainties:
CO_2 Fertilization Effect on Ecosystem Sink
Rate of Carbon Uptake by Deep-Ocean
Trends in Rainfall Frequency on natural CH_4 & N_2O emissions

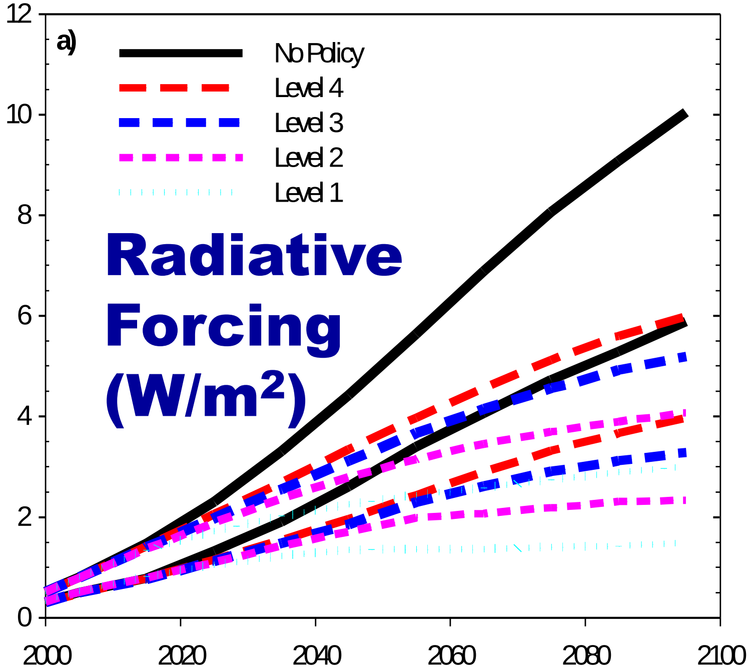
Five Cases indicated by GHG levels (ppm-equivalent CO_2, ppm CO_2 and change in Radiative Forcing relative to ~1990 (W/m^2) in ~2100:

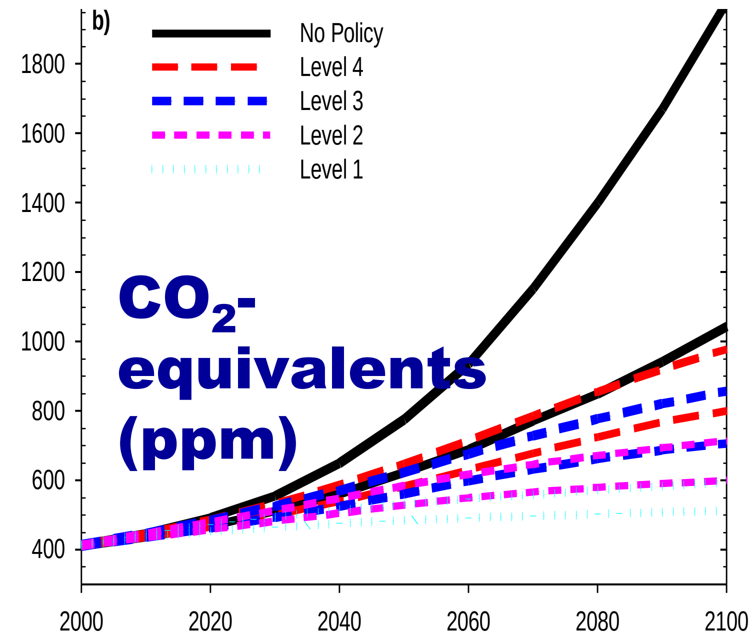
No Policy (1400 ppm CO_2-eq; 870 ppm CO_2; 9.7 W/m^2)
Level 4 (900 ppm CO_2-eq; 710 ppm CO_2; 7.1 W/m^2)
Level 3 (790 ppm CO_2-eq; 640 ppm CO_2; 6.3 W/m^2)
Level 2 (660 ppm CO_2-eq; 560 ppm CO_2; 5.3 W/m^2)
Level 1 (550 ppm CO_2-eq; 480 ppm CO_2; 4.2 W/m^2)

Generate 400 member ensembles (Monte Carlo with Latin Hypercube Sampling) for each case

95% PROBABILITY BOUNDS OF GLOBAL AVERAGE GHG MOLE FRACTIONS AND RADIATIVE FORCING from 1981-2000 to 2090-2100, WITHOUT (1400 ppm-eq CO_2) & WITH A 550, 660, 790 or 900 ppm-eq CO_2 GHG STABILIZATION POLICY?





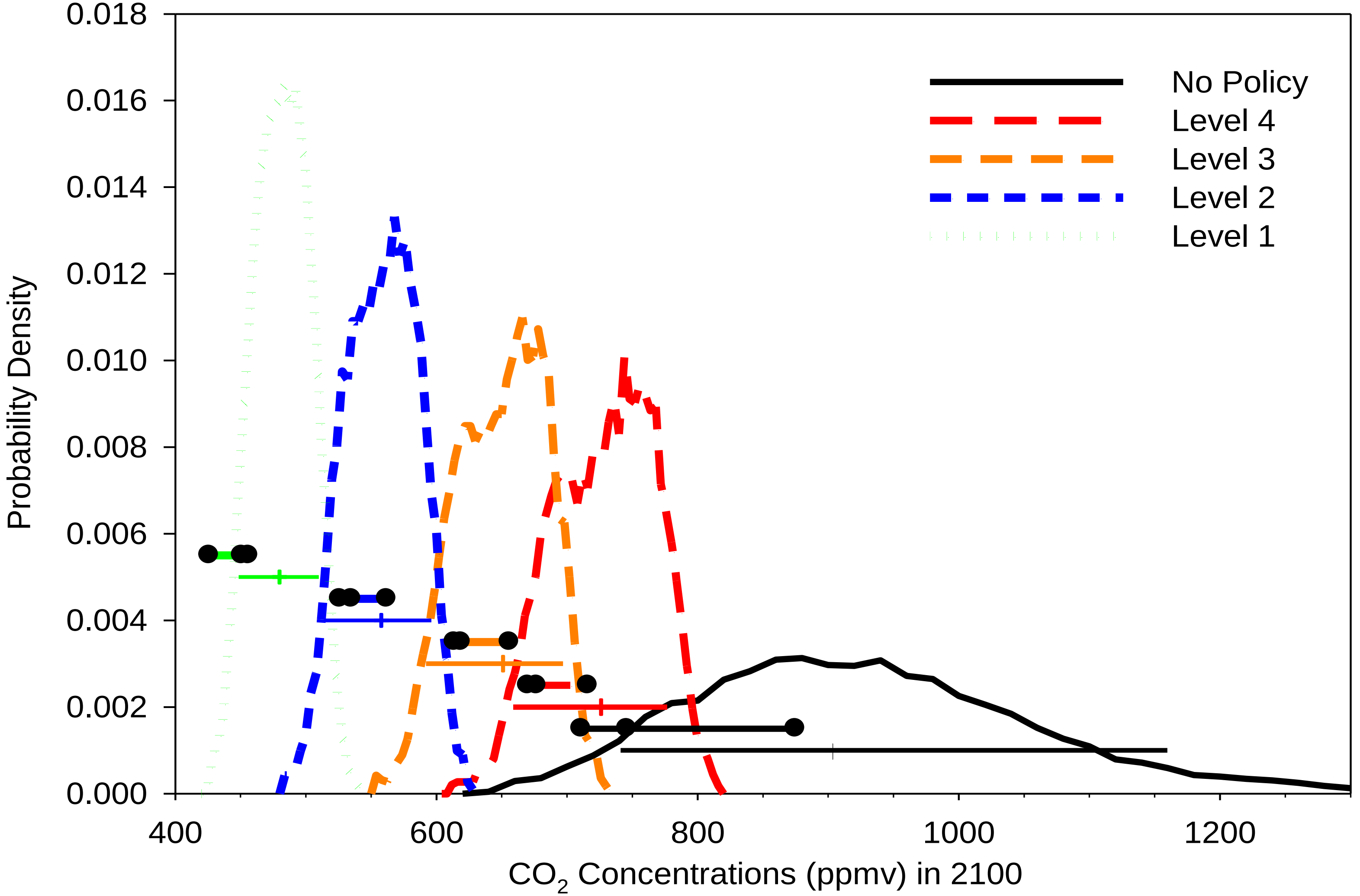


Cumulative PROBABILITY OF GLOBAL AVERAGE SURFACE AIR WARMING from 1981-2000 to 2091-2100, WITHOUT (1400 ppm-eq CO_2) & WITH A 550, 660, 790 or 900 ppm-equivalent CO_2 GHG STABILIZATION POLICY

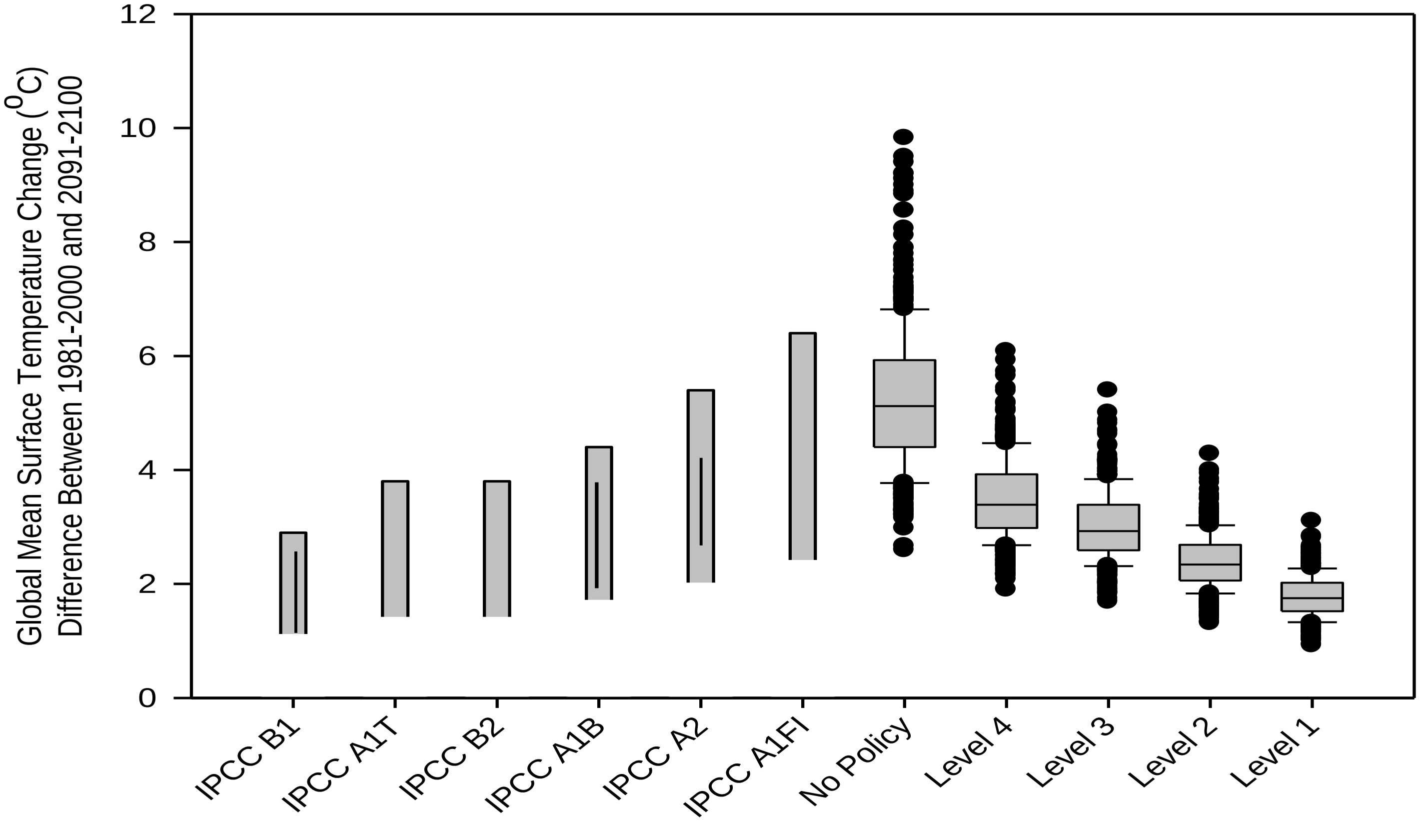
(Ref: Sokolov et al, Journal of Climate, 2009)

	ΔT > 2°C (*Values relative to 1860/pre-industrial)	ΔT > 4°C	ΔT > 6°C
No Policy at 1400	100%(*100%)	85%	25%
Stabilize at 900 (L4)	100%(*100%)	25%	0.25%
Stabilize at 790 (L3)	97%(100%)	7%	< 0.25%
Stabilize at 660 (L2)	80%(*97%)	0.25%	< 0.25%
Stabilize at 550 (L1)	25%(*80%)	< 0.25%	< 0.25%

Comparison to Range in CCSP 2.1A

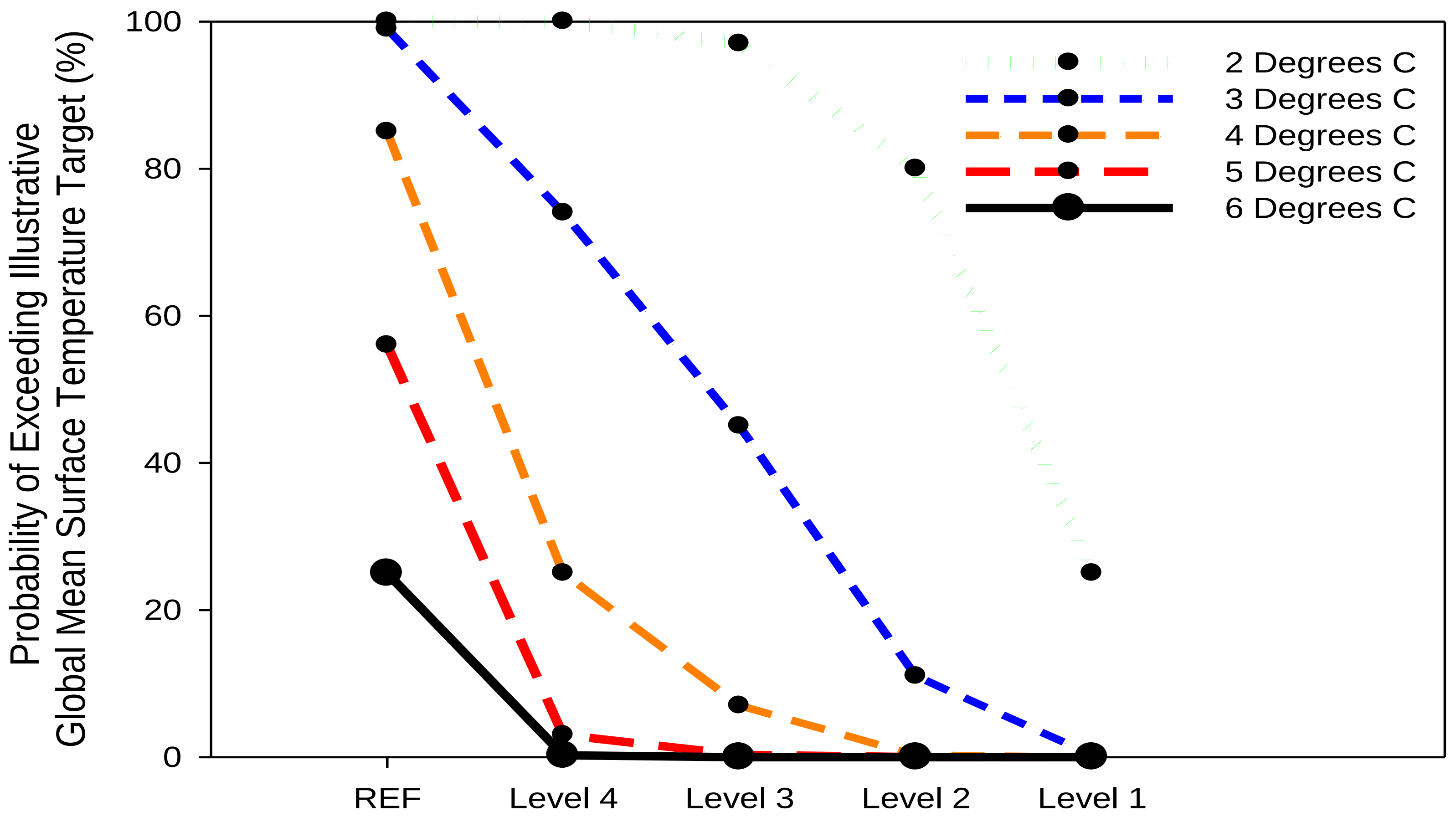


Comparison to IPCC

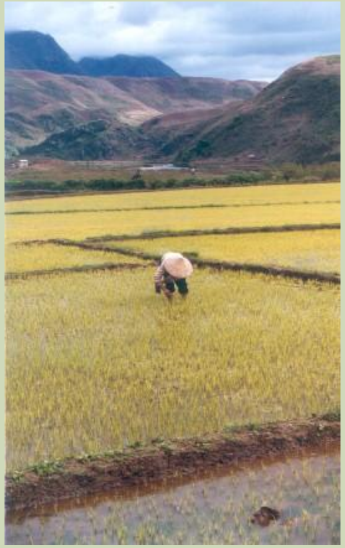


Global mean temperature change (from 1981-2000 to 2091-2100); IPCC SRES scenarios (Meehl et al. 2007). Grey bars for IPCC results indicate 66% and 90% probability), and solid black line indicates the 5-95% range of AOGCM results (only provided for B1, A1B, and A2). This analysis shown as box plots, where box indicates the 50% range, median, outer whiskers indicate the 5-95% range, dots individual outliers beyond the 95% bounds.

Change in the probability of exceeding illustrative targets for global mean surface temperature change, as measured by the change between the average for 1981-2000 and the average for 2091-2100.



The Global Adaptation Atlas




Establishing Priorities for Research, Policy and Action on Adaptation

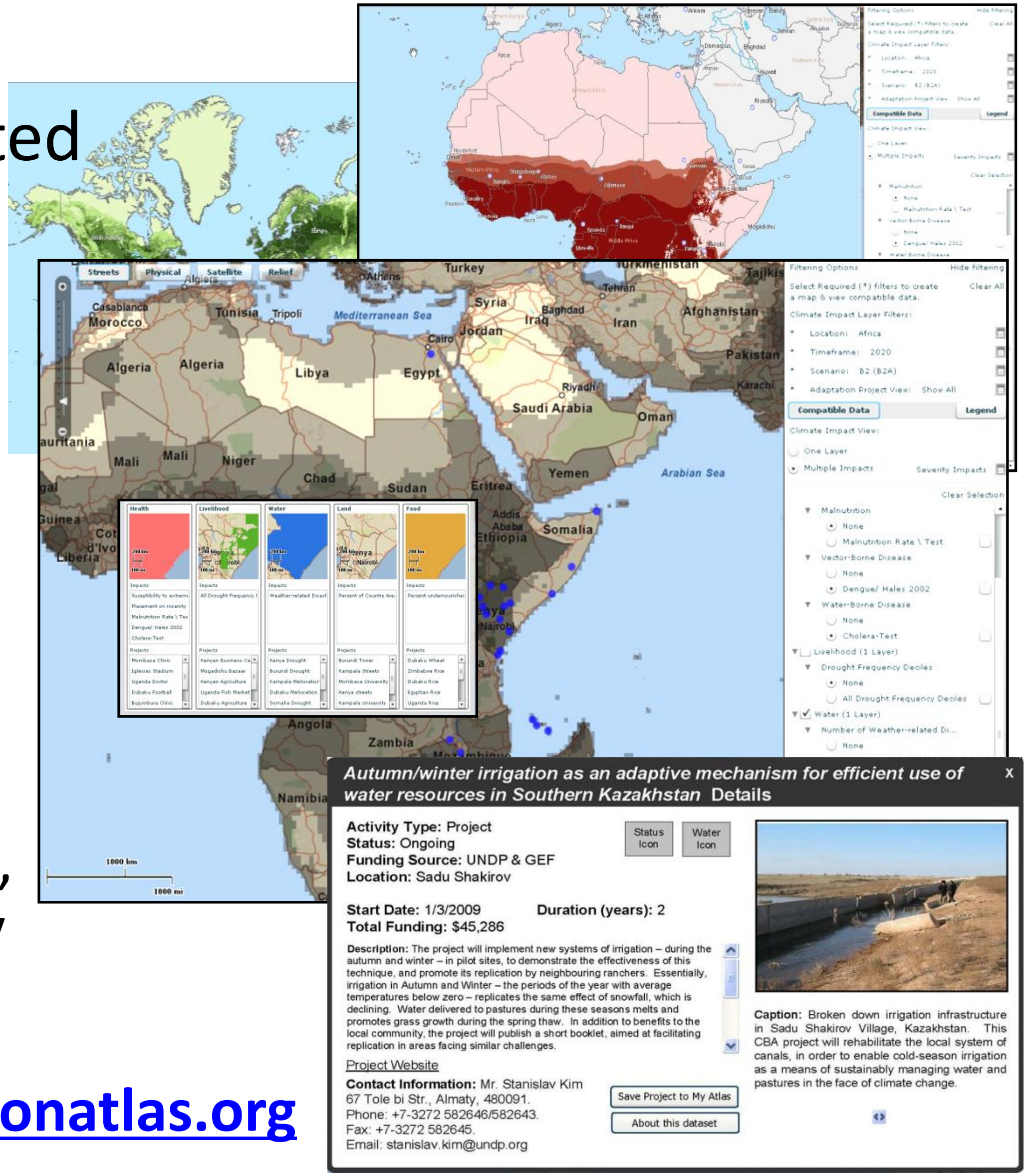
Ray Kopp – Senior Fellow and Director, Climate Policy Program
Nisha Krishnan – Former Atlas Team Member

Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis- November 18-19, 2010

RESOURCES FOR THE FUTURE

What is the Adaptation Atlas?

- Web-based application enables user driven, dynamically generated maps of climate impacts and adaptation activities:
  - Database of impacts from peer reviewed climate studies
  - Repository of adaptation projects
  - Data available for download and uploads of new data supported
  - User can select different locations, timeframes, scenarios and overlay resulting data across sectors



Beta version available at www.adaptationatlas.org

RESOURCES
FOR THE FUTURE

Methodological Questions

1. Data Solicitation and Collection
   - Literature searches
   - Individual author solicitation
2. Study Harmonization/ Comparability
   - Each study is its own story
   - ‘meta’ filters
3. Atlas Outputs

RESOURCES FOR THE FUTURE

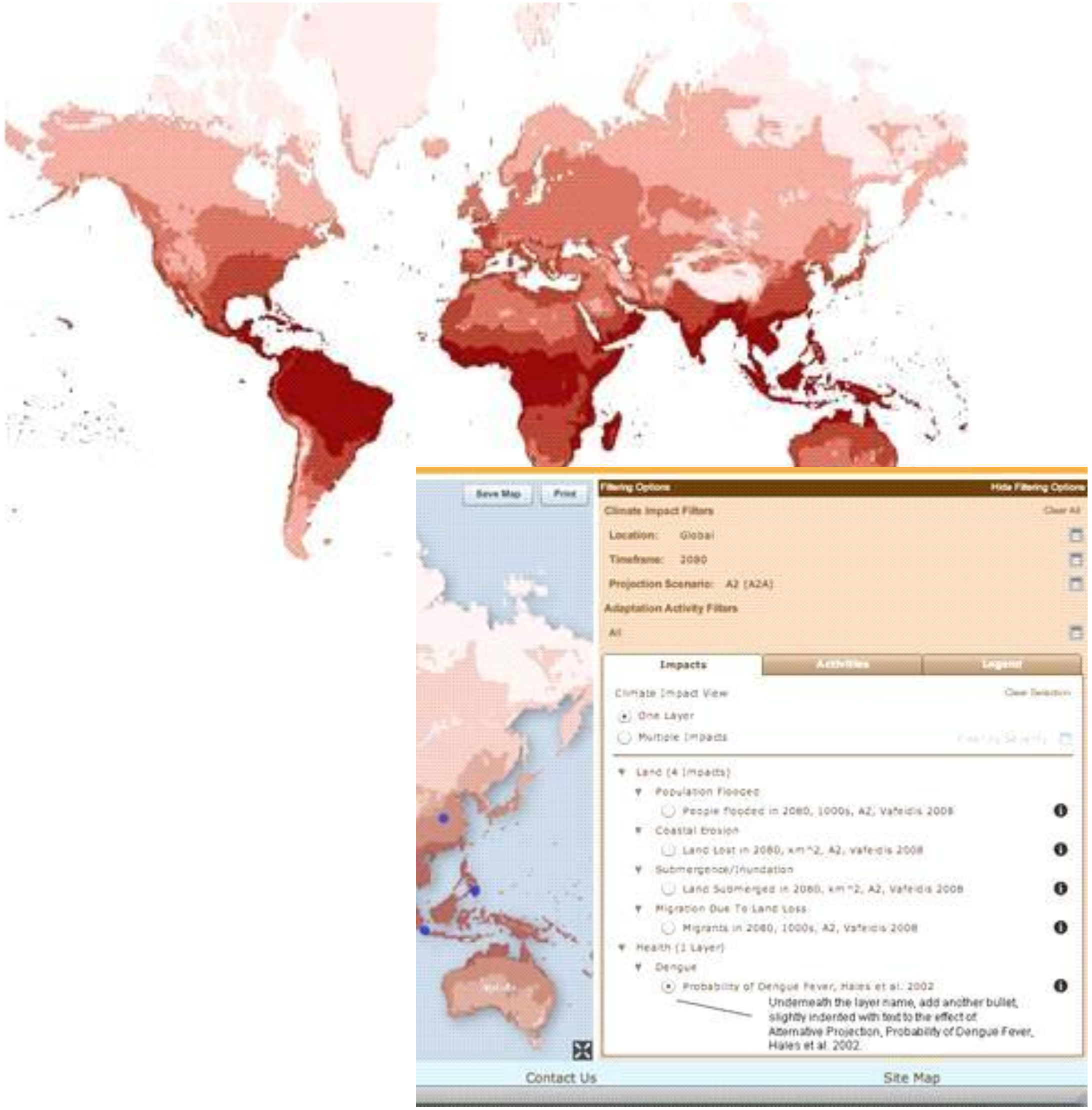
The Uncertainty Issue

- Hales et al. 2002, “Potential Effect of Population and Climate Changes on Global Distribution of Dengue Fever: an Empirical Model”

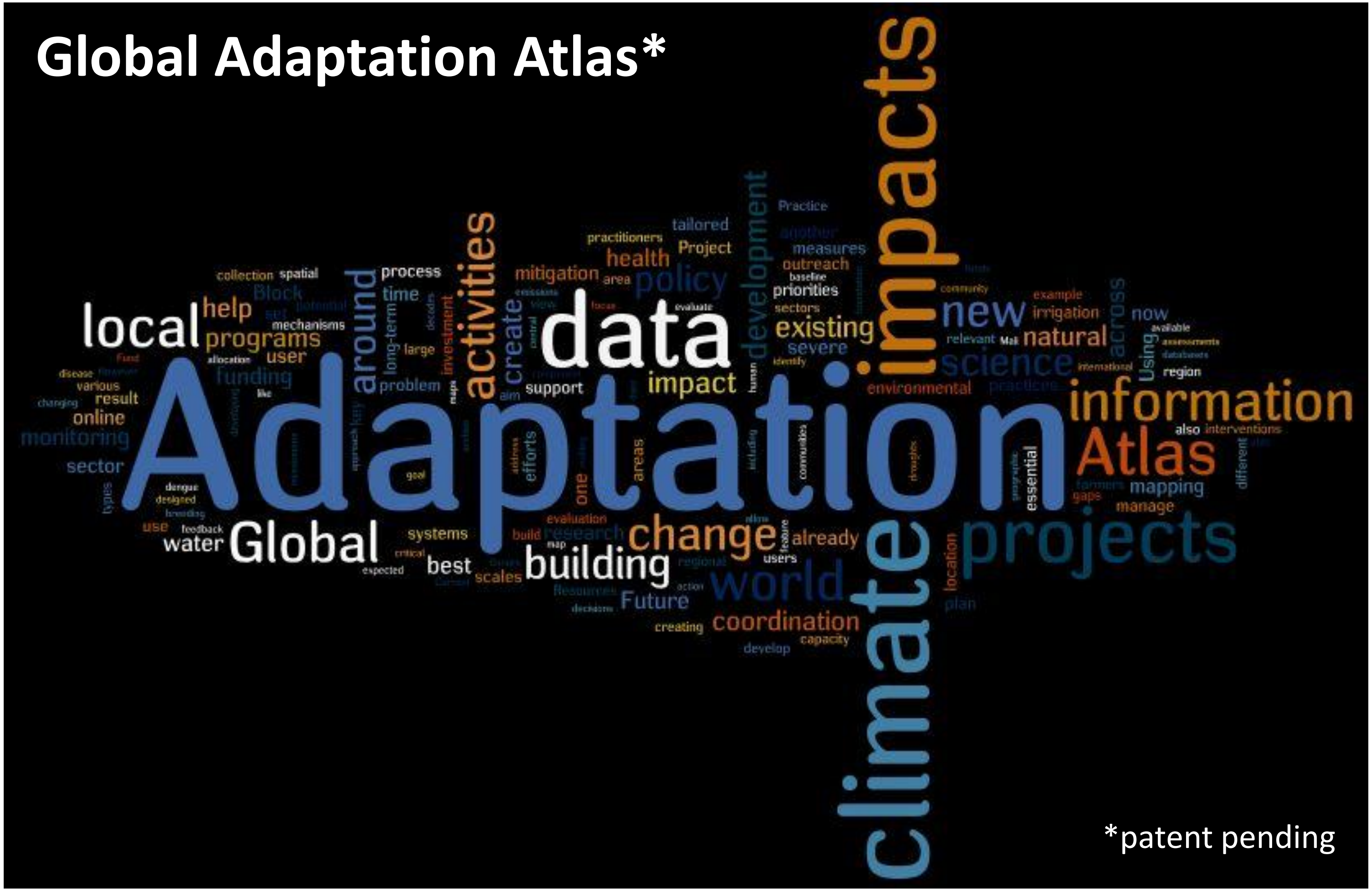
- 4 sets of sensitivity analyses using the ECHAM4, CGCMA1, CGCMA2 and CCSR/NIES models.

- Unique layers that fit into the decision framework of the Atlas.

- Differences between dealing with sensitivity analyses and uncertainty analyses.



RESOURCES FOR THE FUTURE



For more on the Atlas, visit www.adaptationatlas.org or email us at info@adaptationatlas.org

RESOURCES
FOR THE FUTURE

created using wordle.net

A Generalized Modeling Framework for Climate Change Damage Assessment

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NATIONAL CENTER FOR
ENVIRONMENTAL ECONOMICS

Lessons Learned

- Need a more transparent representation of the pathways through which climate change may affect economic productivity and human well-being
- Need a transparent method of incorporating new research on climate damages into modeling exercises
- Desire to more transparently map assumptions of economic behavior (e.g., adaptation, technology diffusion) into economic damage estimates
- Need for reduced form IAMs that allow for a relatively timely assessment in a probabilistic fashion

Reasons for a New Framework

- Help facilitate the process of incorporating new climate science and economic damage research
- To clearly distinguish among damages to market sectors, physical and natural capital stocks, and human health while also accounting for defensive expenditures[¤]
- Standardization so that the effects of specific assumptions/pieces may be better understood
- Increased transparency through complete, accurate, and up-to-date documentation and open source code
- To make climate-economic integrated modeling more accessible to government and researchers

[¤] Defensive expenditures is used here to refer to expenditures borne in order to offset the effects of worsening environmental quality.

Key Characteristics of Framework

- **General** structure that nests commonly used integrated assessment models, including the three used by the interagency workgroup
- **Flexible** framework so that new findings and assumptions may be easily incorporated
- **Transparent**, in that the code, framework, calibrations, and assumptions will be well documented and freely accessible to researchers and other interested parties
- **Probabilistic**, to allow for formal uncertainty analysis in a Monte Carlo framework
- **Modular** design allows for linkage with multiple climate models and future additions of new impact categories
  - For example: Would allow for standardization in climate and economic assumptions across various calibrations of the damage functions (and vice versa)

Overview of Structure

- Climate model coupled to a regionalized exogenous growth model of the economy
- Exogenous technical progress and population growth (potential for climate-population feedbacks)
- Currently uses exogenous emissions scenarios (retains the option for endogenous emissions in the future)
- Currently uses MAGICC as the climate model (may use others; such as those included in DICE, FUND, and PAGE)
- Ability for natural capital to be represented
- Setup to run probabilistically

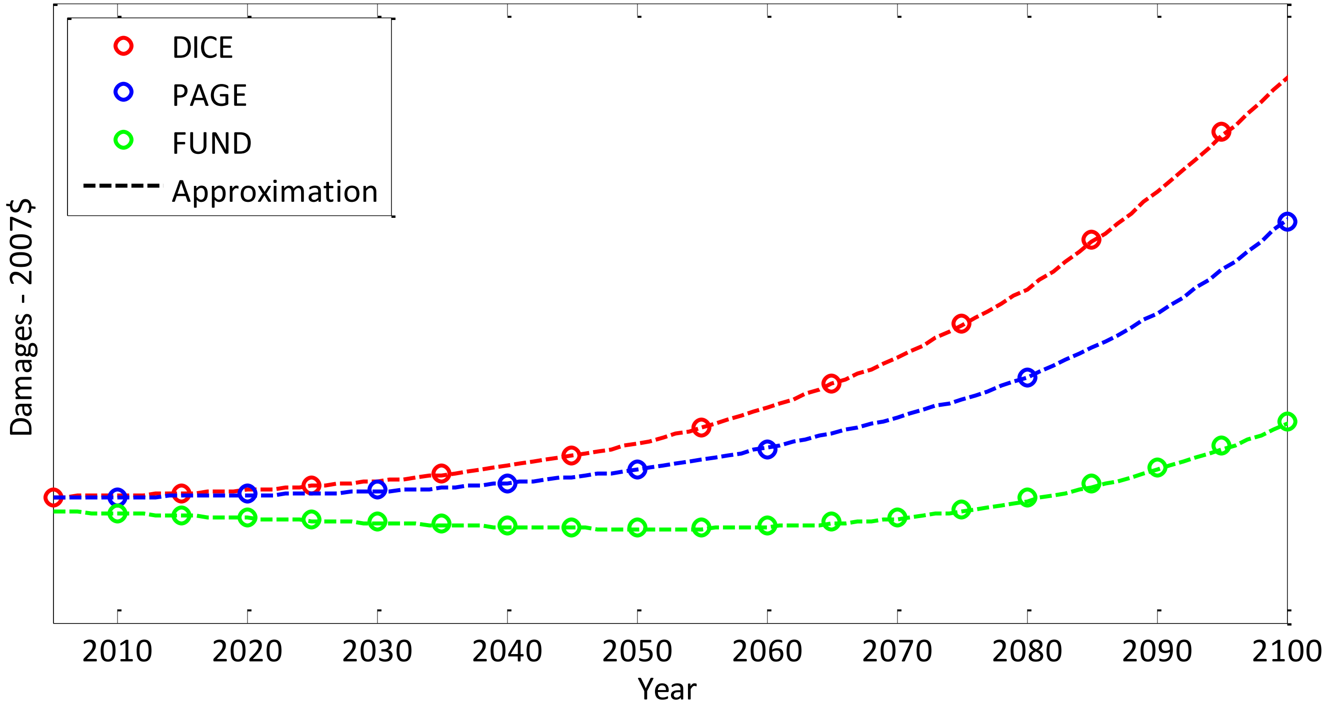
Representation of Damages

- Distinguishes between different types of climate change damages to provide for transparency and ensure that they are affecting the correct end points in the model
  - Damages to multiple market sectors
  - Damages directly to physical capital
  - Defensive expenditures offsetting investment in physical capital
  - Defensive expenditures offsetting household consumption
  - Consumption equivalent health damages
  - Consumption equivalent recreation and nonuse damages
- Use of general functional forms so that the model remains flexible

Current Status

- Prototyping of framework and initial testing
  - Development of initial code base
  - Including interface for public version of MAGICC, along with versions of the DICE, FUND, and PAGE climate models
- Ongoing development of clear and accurate documentation for the framework
- Testing generality by using specific settings to closely approximate versions of DICE, PAGE, and FUND similar to those used by the interagency workgroup

Approximation of Other Models



- The central values of parameters are used in this exercise
- Approximation of FUND does not yet include all the damage sectors that are in the full model

Next Steps

- Continual refinement of the model in response to prototyping
- Full approximation of FUND
- Incorporation of feedback from workshops
- Starting from the studies currently used in existing IAMs move forward with incorporating new studies on climate change damages
- External peer review
- Eventual public release

Modeling the Impacts of Climate Change: Elements of a Research Agenda

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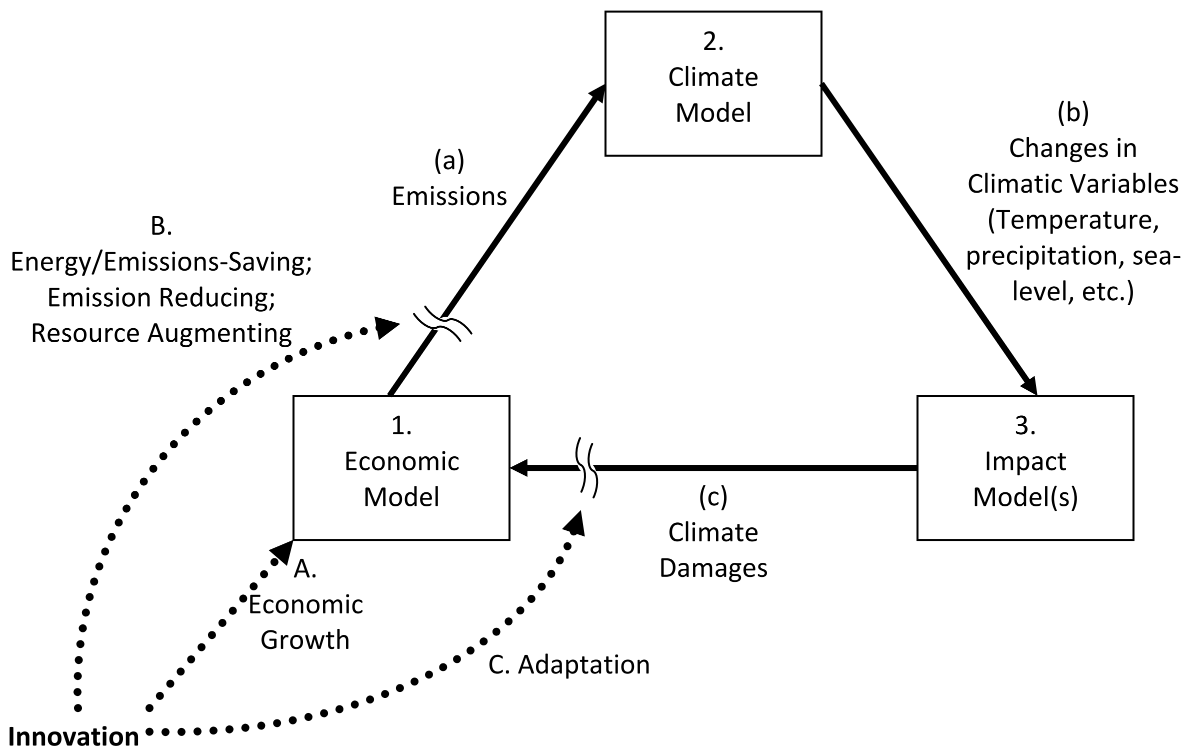
Abstract

1 Introduction: What is an IAM?

As illustrated in Figure 1, an integrated assessment model (IAM) of climate change is typically constructed from three interlinked sub-models, an economic model (1), a climate model (2) and an impacts model (3). It is logical to begin with the economic sub-model, which is responsible for generating time-paths of global emissions of greenhouse gases (GHGs—principally carbon dioxide, CO_2) (a). These serve as inputs to the climate sub-model, which uses them to project changes in the magnitude of meteorological variables such as temperature, precipitation or sea level rise (b). Finally, the changes in climate parameters are translated into projections of global- or regional-scale economic losses by an impacts sub-model, whose primary role is to capture the feedback effect of dangerous near-term anthropogenic interference with the climate on economic activity over the long-term future (c).

Innovation is a key modulator of the clockwise circulation of the feedback loop in the figure. Improvements in the productivity of labor induce more rapid growth and increase the demand for fossil energy resources, which has a first-order amplifying effect on emissions (A). Energy- or emissions-saving technological progress tends to depress the emission intensity of the economy, slowing the rate of increase in fossil fuel use; conversely, productivity improvements in energy resource extraction lower the price of fossil fuels and induce substitution toward them, increasing emissions (B). Lastly, we can imagine that there may be innovations that boost the effectiveness of defensive expenditures undertaken in response to the threat of climate damages, or investments in creating new knowledge that enables humankind to mitigate some climate damages (C). This last category is the most speculative, as impacts will manifest themselves several decades in the future, when the state of technology is likely to be quite different from today.

Figure 1: Integrated Assessment of Climate Change and the Effects of Innovation



2 Land of Cockaigne: An IAM with Regional, Sectoral and Climate Impact Detail

Imagine that there were relatively few constraints to either our computational resources or our ability to foresee the impacts of climate change. In such a world, what would an IAM look like? We could then specify a RICE- or AD-WITCH-type IAM that resolved (a) the detailed sectoral structure of production in various regions, (b) the effects of climate impacts on the productivity of those sectors, (c) the manner in which different impact endpoints combined to generate the resultant productivity effects, and (d) the response of the full range of impacts to changes in climatic variables at regional scale.

Let us write down such a model, and exploit its structure to assess the implications for the social cost of carbon. Define the following nomenclature:

Set indexes:	
$t = \{0, \ldots, \mathscr{T}\}$	Time periods
$\ell = \{1, \ldots, \mathscr{L}\}$	World regions
$j = \{1, \ldots, \mathscr{N}\}$	Industry sectors
$m = \{1, \ldots, \mathscr{M}\}$	Meteorological characteristics
$f = \{1, \ldots, \mathscr{F}\}$	Climate impact endpoints
Control variables:	
$q^E_{j,\ell,t}$	Sectoral energy input
$q^K_{j,\ell,t}$	Sectoral capital input
$Q^C_{\ell,t}$	Aggregate consumption
$Q^I_{\ell,t}$	Aggregate jelly capital investment
$a^f_{j,\ell,t}$	Region-, sector- and impact-specific averting expenditure
$v^f_{j,\ell,t}$	Region-, sector- and impact-specific adaptation investment
Economic state variables:	
$\mathscr{W}$	Welfare (model objective)
$q^Y_{j,\ell,t}$	Net sectoral product
$Q^Y_{\ell,t}$	Aggregate net regional product
$Q^E_{\ell,t}$	aggregate regional energy use
P^E_t	Global marginal energy resource extraction cost

$Q^K_{\ell,t}$	Stock of aggregate jelly capital
$x^f_{j,\ell,t}$	Stock of region-, sector- and impact-specific adaptation capital
Environmental state variables:	
G_t	Global stock of atmospheric GHGs
$M^m_{\ell,t}$	Region-specific meteorological variables
$z^f_{j,\ell,t}$	Region-, sector-, and impact-specific endpoint indexes
$\Lambda_{j,\ell,t}$	Region- and sector-specific damage induced productivity losses
Functional relationships:	
Ξ	Global intertemporal welfare
U_ℓ	Regional intratemporal utility
Φ_ℓ	Regional aggregate production functions
$\psi_{j,\ell}$	Sectoral production functions
Θ	Global energy supply function
$\mathcal{E}$	Global atmospheric GHG accumulation
Υ^m_ℓ	Regional climate response functions
$\zeta^f_{j,\ell}$	Regional and sectoral climate impacts functions
$\lambda_{j,\ell}$	Regional and sectoral damage functions

1. Economic Sub-Model

Objective:

$$\max_{Q^C_{\ell,t}, q^E_{j,\ell,t}, q^K_{j,\ell,t}} \mathscr{W} = \sum_{t=0}^{T} \beta^t \Xi \left[U_1 \left[Q^C_{1,t} \right], \ldots, U_{\mathscr{L}} \left[Q^C_{\mathscr{L},t} \right] \right] \tag{1a}$$

Aggregate net regional product:

$$Q^Y_{\ell,t} = \Phi_\ell \left[q^Y_{1,\ell,t}, \ldots, q^Y_{\mathscr{N},\ell,t} \right] \tag{1b}$$

Sectoral net regional product = Climate loss factor × Sectoral gross regional product, produced from energy and capital:

$$q^Y_{j,\ell,t} = \Lambda_{j,\ell,t} \cdot \psi_{j,\ell} \left[q^E_{j,\ell,t}, q^K_{j,\ell,t} \right] \tag{1c}$$

Intraregional and intratemporal market clearance for energy:

$$\sum_{j=1}^{\mathscr{N}} q^E_{j,\ell,t} = Q^E_{\ell,t} \tag{1d}$$

Intraregional and intratemporal market clearance for jelly capital:

$$\sum_{j=1}^{\mathcal{N}} q^K_{j,\ell,t} = Q^K_{\ell,t} \tag{1e}$$

Aggregate regional absorption constraint:

$$Q^C_{\ell,t} = Q^Y_{\ell,t} - Q^I_{\ell,t} - P^E_t Q^E_{\ell,t} - \sum_{f=1}^{\mathcal{F}} \sum_{j=1}^{\mathcal{N}} \left(a^f_{j,\ell,t} + v^f_{j,\ell,t} \right) \tag{1f}$$

Global energy trade and marginal resource extraction cost:

$$P^E_t = \Theta \left[\sum_{\ell=1}^{\mathcal{L}} \sum_{s=0}^{t} Q^E_{\ell,s} \right] \tag{1g}$$

Regional jelly capital accumulation:

$$Q^K_{\ell,t+1} = Q^I_{\ell,t} + (1 - \vartheta^K) Q^K_{\ell,t} \tag{1h}$$

Accumulation of impact-, sector- and region-specific adaptation capital:

$$x^f_{j,\ell,t+1} = v^f_{j,\ell,t} + (1 - \vartheta^f) x^f_{j,\ell,t} \tag{1i}$$

2. Climate Sub-Model

Global atmospheric GHG accumulation:

$$G_{t+1} = \mathcal{E} \left[\sum_{\ell} Q^E_{\ell,t}, G_t \right] \tag{2a}$$

Regional meteorological effects of global atmospheric GHG concentration:

$$M^m_{\ell,t} = \Upsilon^m_{\ell} \left[G_t \right] \tag{2b}$$

3. Impacts Sub-Model

Physical climate impacts by type, sector and region:

$$z^f_{j,\ell,t} = \zeta^f_{j,\ell} \left[M^1_{1,0}, \ldots, M^{\mathcal{M}}_{1,0}; \ldots; M^1_{\mathcal{L},t}, \ldots, M^{\mathcal{M}}_{\mathcal{L},t} \right] \tag{3a}$$

Climate damages:

$$\Lambda_{j,\ell,t} = \lambda_{j,\ell} \left[z^1_{j,\ell,t}, \ldots, z^{\mathcal{F}}_{j,\ell,t}; a^1_{j,\ell,t}, \ldots, a^{\mathcal{F}}_{j,\ell,t}; x^1_{j,\ell,t}, \ldots, x^{\mathcal{F}}_{j,\ell,t} \right] \tag{3b}$$

From the point of view of period $t^\star$, the condition for optimal extraction of carbon-energy is:

$$\frac{\partial \mathscr{W}}{\partial Q^E_{\ell^\star,t^\star}} \Bigg/ \frac{\partial \mathscr{W}}{\partial Q^C_{\ell^\star,t^\star}} = \underbrace{\sum_{j=1}^{\mathscr{N}} \left(\frac{\partial \phi_{\ell^\star}}{\partial q^Y_{j,\ell^\star,t^\star}} \frac{\partial \psi_{j,\ell^\star}}{\partial q^E_{j,\ell^\star,t^\star}} \frac{\partial q^E_{j,\ell^\star,t^\star}}{\partial Q^E_{\ell^\star,t^\star}} \right)}_{\text{I. Current marginal benefit}} - \underbrace{P^E_{t^\star}}_{\substack{\text{II. Current marginal} \\ \text{extraction cost}}}$$
$$- \underbrace{\sum_{t=t^\star}^{T} \beta^{t-t^\star} \sum_{\ell=1}^{\mathscr{L}} \left(\frac{\partial \Xi}{\partial U_\ell} \frac{\partial U_\ell}{\partial Q^C_{\ell,t}} \frac{\partial \Theta}{\partial Q^E_{\ell^\star,t^\star}} Q^E_{\ell,t} \right) \Bigg/ \left(\frac{\partial \Xi}{\partial U_{\ell^\star}} \frac{\partial U_{\ell^\star}}{\partial Q^C_{\ell^\star,t^\star}} \right)}_{\text{III. Resource stock effect of contemporaneous energy use}}$$
$$\underbrace{\begin{aligned} &+ \sum_{t=t^\star+1}^{T} \beta^{t-t^\star} \frac{\partial \mathcal{E}}{\partial Q^E_{\ell^\star,t^\star}} \Bigg/ \left(\frac{\partial \Xi}{\partial U_{\ell^\star}} \frac{\partial U_{\ell^\star}}{\partial Q^C_{\ell^\star,t^\star}} \right) \\ &\quad \times \sum_{\ell=1}^{\mathscr{L}} \left\langle \frac{\partial \Xi}{\partial U_\ell} \frac{\partial U_\ell}{\partial Q^C_{\ell,t}} \sum_{j=1}^{\mathscr{N}} \left\{ \frac{\partial \phi_\ell}{\partial q^Y_{j,\ell,t}} \psi_{j,\ell,t} \sum_{f=1}^{\mathscr{F}} \left[\frac{\partial \lambda_{j,\ell}}{\partial z^f_{j,\ell,t}} \sum_{m=1}^{\mathscr{M}} \left(\frac{\partial \zeta^f_{j,\ell}}{\partial M^m_{\ell,t}} \frac{\partial \mathrm{Y}^m_\ell}{\partial G_t} \right) \right] \right\} \right\rangle \end{aligned}}_{\text{IV. Present value of future marginal climate damage (N.B. } \partial q^Y/\partial \Lambda < 0 \text{ in general)}}$$
$$= 0 \tag{4}$$

The "social cost of carbon" in this expression is given by the combination of terms (II) + (III) - (IV). Our interest is in (IV), the marginal external cost of carbon-energy consumption, which, because it emanates from a globally well-mixed pollutant, is independent of the location in which the energy is consumed.

It is now clear to see how fundamental gaps in our understanding the render the "land of cockaigne" unattainable. The difficulty in computing the social cost of carbon stems from the terms in curly braces. Carbon-cycle modeling is sufficiently advanced to enable us to predict with a fair degree of confidence the effect of the marginal ton of carbon on the time-path of future atmospheric GHGs ($\partial \mathcal{E}/\partial Q^E$). Likewise, the IPCC AR4 notes global climate models' substantially improved ability to capture the future trajectory of consequent changes in temperature, precipitation, ice/snow cover and sea levels at regional scales ($\partial \mathrm{Y}^m_\ell/\partial G$). But the weak links in the causal chain between climate change and economic damages continue to be the cardinality and magnitude of the vectors of physical impact endpoints as a function of climatic variables in each region out into the future

$(\partial \zeta^{f}_{j,\ell} / \partial M^{m}_{\ell})$, and—to a lesser extent—the manner in which these endpoints translate into shocks to the productivity of economic sectors $(\partial \lambda_{j,\ell} / \partial z^{f}_{j,\ell})$.

3 A Critical Review of the State of Modeling Practice

To put the key issues in sharp relief, it is useful to consider how implementing the disaggregated IAM might improve upon the current state of integrated assessment practice. RICE-type IAMs represent the productivity losses incurred by climate change impacts through variants of Nordhaus' aggregate damage function, which specifies the reduction in gross regional product as a function of global mean temperature. This approach effectively collapses M^{m}_{ℓ} to a scalar quantity in each time period. Moreover, as reviewed by NRC (2010), it then benchmarks the magnitude of various impacts and the associated economic losses for a reference level of global mean temperature change, before making assumptions about how these costs are likely to scale with income, and finally expressing damage as a temperature-dependent fraction of regions' gross output. Therefore, the details of climatic variables' influence on impact endpoints in (3a), and of the latter's effects on economic sectors in (3b), only affect the calibration of the damage function. From that point on they are entirely subsumed within the function's elasticity with respect to global temperature change, and, in RICE-2010, sea level rise. The damage function therefore collapses (3a) into (3b), dealing only with changes in aggregate global climatic variables, skipping over impacts as state variables and implicitly aggregating over sectors to express damages purely on an aggregate regional basis.

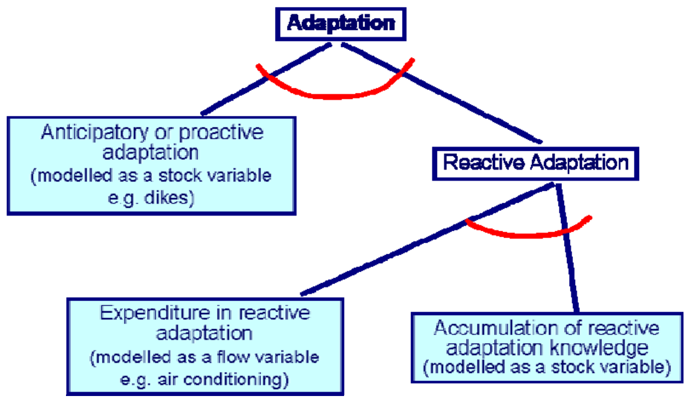
A similar situation obtains with adaptation. A case in point is the AD-WITCH model, a variant of Nordhaus' RICE simulation which modifies the damage function by introducing stock and flow adaptation expenditures which attenuate aggregate regional productivity losses due to climate change. Formally, using $\widetilde{Q}^{Y}$ to denote gross regional product, net regional product is given by

$$Q_{\ell,t}^{Y} = \frac{1 + ADAPT_{\ell,t}}{1 + ADAPT_{\ell,t} + CCD_{\ell,t}} \widetilde{Q}_{\ell,t}^{Y} \tag{5}$$

where CCD is the regional climate damage function and $ADAPT$ is an index of adaptation's effectiveness. The variable $ADAPT$ is the output of a nested constant elasticity of substitution (CES) production function which combines inputs of contemporaneous averting expenditures with adaptation capital and adaptation knowledge according to Figure 2. The key consequence is that adaptation is able to directly influence the dynamic path of the economy, instead of being implicit in the curvature of the damage function, as with the RICE model. However, eq. (5)'s assumption that the effects of $ADAPT$ and CCD are multiplicative seems very strong in light of the fact that the damage function already explicitly incorporates the influence of adaptation through the studies on which it is benchmarked—but only at the calibration point, not over the full range of its curvature. A prime example is Nordhaus and Boyer's (2000) use of Yohe and Schlesinger's (1998) results on the impact of sea level rise, which optimally balance the costs of abandonment and coastal defenses. The implication is that because defensive expenditures are likely to be closely associated with the magnitudes of climate impacts of various kinds within individual sectors, one should not think of aggregate adaptation expenditure as independent of future changes in the sectoral composition of output.

By dispensing with the aggregate damage function, our land of cockaigne IAM explicitly captures the dynamic evolution of impact endpoints' response to changes in climatic variables, the magnitude and intersectoral distribution of the follow-on productivity effects, and the optimal intersectoral adjustments these induce, all at regional scales. An adaptation response may therefore be modeled more precisely as averting expenditure that mitigates the sectoral and regional productivity loss associated with a particular category of climate impact. In other words, stock and flow adaptation reduces the impact

Figure 2: The AD-WITCH Adaptation Production Function (Bosello, Carraro and De Cian, 2010)



elasticity of sectoral productivity shocks. Of course, the problem that besets this approach is that, except for a very few combinations of impacts, sectors and regions, the relevant elasticities are unknown.

But the good news is that this is one area in which research is proceeding apace. There are a growing number of CGE modeling studies of climate impacts (e.g., ICES) which elucidate the magnitude of both sectoral and regional damages and producers' and consumers' adjustment responses. The focus of such studies is typically a single impact category (say, $f^{\star}$), whose initial economic effects are computed using natural science or engineering modeling or statistical analyses. The results are often expressed as a vector of shocks to exposed sectors and regions, which are then imposed as exogenous productivity declines on the CGE models' cost functions. In the context of the IAM in section 2, this procedure is equivalent to first specifying an exogenous ex-ante effect of a particular impact $\overline{\partial\lambda_{j,\ell}/\partial z^{f^{\star}}_{j,\ell}}$, before using the CGE model to compute the ex-post web of intersectoral adjustments and the consequences for sectoral output, and regions' aggregate net product and welfare:

$$\frac{\partial U_{\ell}}{\partial Q^{C}_{\ell,t}} \sum_{j=1}^{\mathcal{N}} \left(\frac{\partial \phi_{\ell}}{\partial q^{Y}_{j,\ell,t}} \psi_{j,\ell,t} \frac{\overline{\partial \lambda_{j,\ell}}}{\partial z^{f^{\star}}_{j,\ell}} \right).$$

This line of inquiry has the potential to yield two critical insights. The first is quantification of the elasticity of the economy's response to variations in the magnitude and inter-regional/intersectoral distribution of particular types of impact, which has been the type of investigation pursued thus far. But second—and arguably more important—is comparative analysis of economic responses *across* different impact categories for the purpose of establishing their relative overall economic effect, conditional on our limited knowledge of their relative likelihood of occurrence, and intensity. The results could at the very least guide the allocation of effort in investigating the thorny question of how different impacts are likely to respond to climatic forcings at the regional scale, $\partial \zeta^{f}_{j,\ell} / \partial M^{m}_{\ell}$.

Sectoral and Regional Disaggregation and Interactions

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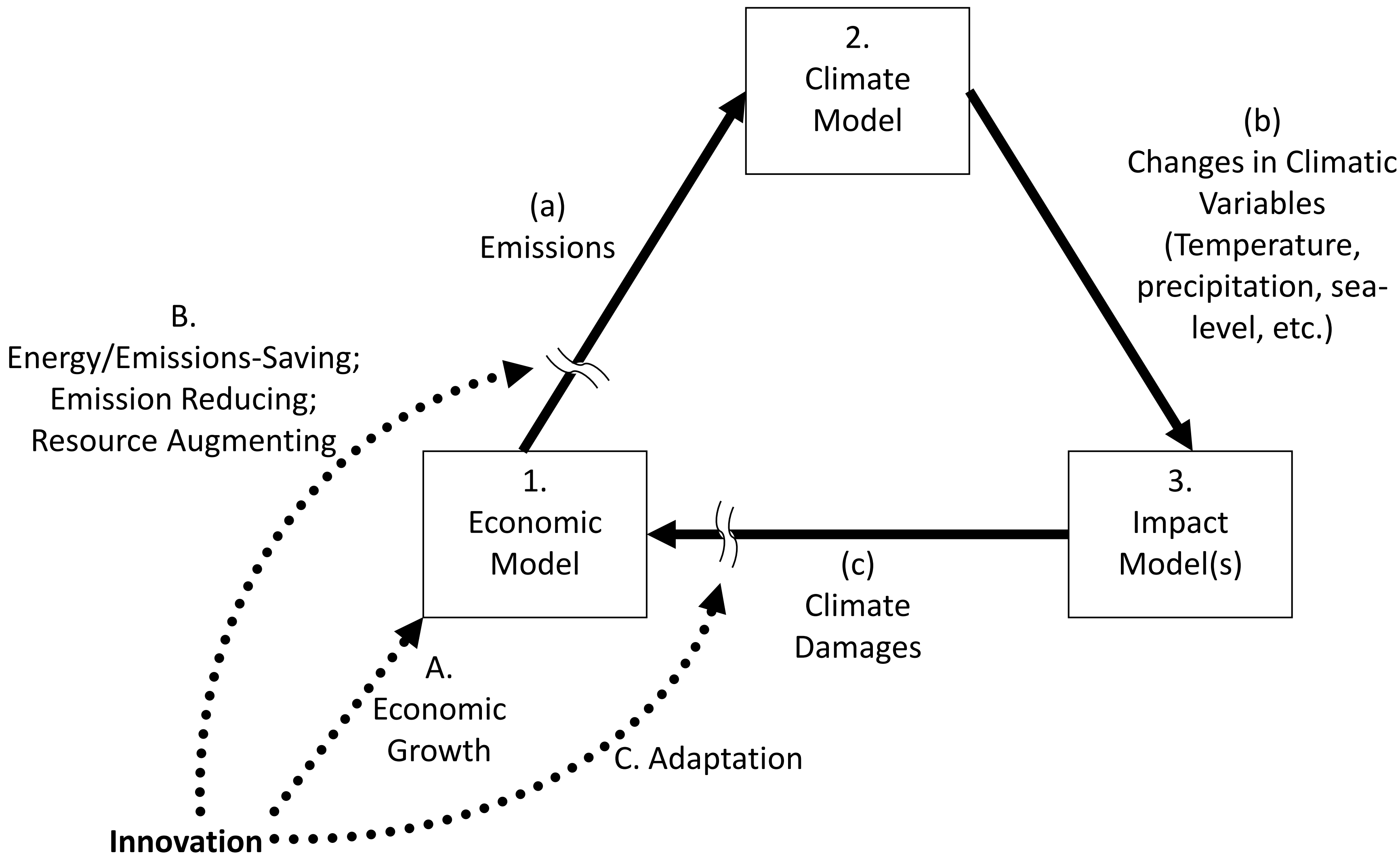
Boston University

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

Nov. 18-19, 2010

What Is an Integrated Assessment Model?



Desiderata in Model Development:

If neither empirical estimates nor computational resources were an issue, what kind of IAM would we construct?

A Canonical Intertemporal IAM

Welfare: $\max \sum_r \sum_{t=\{0,\ldots,T\}} \phi_{r,t} \cdot \beta^t \cdot \mathcal{U}_r[C_{1,r,t}, C_{2,r,t}, \ldots]$

Sectoral Output: $Q_{j,r,t} = A_{j,r,t} \cdot \mathcal{F}_{j,r}[K_{j,r,t}, E_{j,r,t}]$

Absorption: $Q_{j,r,t} = C_{j,r,t} + I_{j,r,t} + \mathcal{P}[X_t] \cdot E_{j,r,t}$

Energy Extraction: $X_{t+1} = \sum_j \sum_r E_{j,r,s} + X_t$

Capital Accum.: $K_{j,r,t+1} = \psi_{j,r} \cdot \sum_{j'} I_{j',r,t} + (1 - \delta) K_{j,r,t}$

Carbon Cycle: $G_{\rho,t+1} = \mathcal{H}_\rho[\sum_j \sum_r E_{j,r,t}, G_{\rho,t}]$

Regional Climate: $M_{\mu,r,t} = \mathcal{M}_{\mu,r}[G_{1,t}, G_{2,t}, \ldots]$

Regional Impacts: $Z_{i,j,r,t} = \Omega_{i,j,r}[M_{1,r,t}, M_{2,r,t}, \ldots]$

Regional Damage: $A_{j,r,t} = \Delta_{j,r}[Z_{1,j,r,t}, Z_{2,j,r,t}, \ldots]$

A Canonical Intertemporal IAM

1. Economy

Welfare: max $\sum_r \sum_{t=\{0,\ldots,T\}} \phi_{r,t} \cdot \beta^t \cdot \mathcal{U}_r[C_{1,r,t}, C_{2,r,t}, \ldots]$

Sectoral Output: $Q_{j,r,t} = A_{j,r,t} \cdot \mathcal{F}_{j,r}[K_{j,r,t}, E_{j,r,t}]$

Absorption: $Q_{j,r,t} = C_{j,r,t} + I_{j,r,t} + \mathcal{T}[X_t] \cdot E_{j,r,t}$

Energy Extraction: $X_{t+1} = \sum_j \sum_r E_{j,r,s} + X_t$

Capital Accum.: $K_{j,r,t+1} = \psi_{j,r} \cdot \sum_{j'} I_{j',r,t} + (1 - \delta) K_{j,r,t}$

Carbon Cycle: $G_{\rho,t+1} = \mathcal{H}_\rho[\sum_j \sum_r E_{j,r,t}, G_{\rho,t}]$

Regional Climate: $M_{\mu,r,t} = \mathcal{M}_{\mu,r}[G_{1,t}, G_{2,t}, \ldots]$

Regional Impacts: $Z_{i,j,r,t} = \Omega_{i,j,r}[M_{1,r,t}, M_{2,r,t}, \ldots]$

Regional Damage: $A_{j,r,t} = \Delta_{j,r}[Z_{1,j,r,t}, Z_{2,j,r,t}, \ldots]$

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Carbon Cycle: $G_{\rho,t+1} = \mathcal{H}_\rho[\sum_j \sum_r E_{j,r,t}, G_{\rho,t}]$

Regional Climate: $M_{\mu,r,t} = \mathcal{M}_{\mu,r}[G_{1,t}, G_{2,t}, \ldots]$

2. Climate

Regional Impacts: $Z_{i,j,r,t} = \Omega_{i,j,r}[M_{1,r,t}, M_{2,r,t}, \ldots]$

Regional Damage: $A_{j,r,t} = \Delta_{j,r}[Z_{1,j,r,t}, Z_{2,j,r,t}, \ldots]$

A Canonical Intertemporal IAM

Welfare: $\max \sum_r \sum_{t=\{0,\ldots,T\}} \phi_{r,t} \cdot \beta^t \cdot \mathcal{U}_r[C_{1,r,t}, C_{2,r,t}, \ldots]$

Sectoral Output: $Q_{j,r,t} = A_{j,r,t} \cdot \mathcal{F}_{j,r}[K_{j,r,t}, E_{j,r,t}]$

Absorption: $Q_{j,r,t} = C_{j,r,t} + I_{j,r,t} + \mathcal{T}\!\mathcal{I}[X_t] \cdot E_{j,r,t}$

Energy Extraction: $X_{t+1} = \sum_j \sum_r E_{j,r,s} + X_t$

Capital Accum.: $K_{j,r,t+1} = \psi_{j,r} \cdot \sum_{j'} I_{j',r,t} + (1 - \delta)\, K_{j,r,t}$

Carbon Cycle: $G_{\rho,t+1} = \mathcal{H}_\rho[\sum_j \sum_r E_{j,r,t}, G_{\rho,t}]$

Regional Climate: $M_{\mu,r,t} = \mathcal{M}_{\mu,r}[G_{1,t}, G_{2,t}, \ldots]$

Regional Impacts: $Z_{i,j,r,t} = \Omega_{i,j,r}[M_{1,r,t}, M_{2,r,t}, \ldots]$

Regional Damage: $A_{j,r,t} = \Delta_{j,r}[Z_{1,j,r,t}, Z_{2,j,r,t}, \ldots]$

3. Impacts

A Canonical Intertemporal IAM

Welfare: max $\sum_r \sum_{t=\{0,\ldots,T\}} \phi_{r,t} \cdot \beta^t \cdot \mathcal{U}_r[C_{1,r,t}, C_{2,r,t}, \ldots]$

Sectoral Output: $Q_{j,r,t} = A_{j,r,t} \cdot \mathcal{F}_{j,r}[K_{j,r,t}, E_{j,r,t}]$

Absorption: $Q_{j,r,t} = C_{j,r,t} + I_{j,r,t} + \mathcal{P}[X_t] \cdot E_{j,r,t}$

Energy Extraction: $X_{t+1} = \sum_j \sum_r E_{j,r,s} + X_t$

Capital Accum.: $K_{j,r,t+1} = \psi_{j,r} \cdot \sum_{j'} I_{j',r,t} + (1 - \delta)\, K_{j,r,t}$

Carbon Cycle: $G_{\rho,t+1} = \mathcal{H}_\rho[\sum_j \sum_r E_{j,r,t}, G_{\rho,t}]$

Regional Climate: $M_{\mu,r,t} = \mathcal{M}_{\mu,r}[G_{1,t}, G_{2,t}, \ldots]$

Regional Impacts: $Z_{i,j,r,t} = \Omega_{i,j,r}[M_{1,r,t}, M_{2,r,t}, \ldots]$

Regional Damage: $A_{j,r,t} = \Delta_{j,r}[Z_{1,j,r,t}, Z_{2,j,r,t}, \ldots]$

Maximand: Global Intertemporal Welfare Over a Policy Horizon

Welfare: $\max \sum_r \sum_{t=\{0,\dots,T\}} \phi_{r,t} \cdot \beta^t \cdot \mathcal{U}_r[C_{1,r,t}, C_{2,r,t}, \dots]$

Sectoral Output: $Q_{j,r,t} = A_{j,r,t} \cdot \mathcal{F}_{j,r}[K_{j,r,t}, E_{j,r,t}]$

Absorption: $Q_{j,r,t} = C_{j,r,t} + I_{j,r,t} + \Pi[X_t] \cdot \dots_{,t}$

Energy Extr… $X_{t+1} = \sum_j \sum \dots E_{j,r,s} + X_t$

Capital Acc… $K_{j,\dots} = \dots_{j,r} \cdot \sum \dots$

Carbon Cycle: $G \dots \int_\rho [\dots$

Regional Climate: $M_{\mu,r,t} \dots \mathcal{M}_{\mu,r} \dots$

Regional Impacts: $Z_{i,j,r,t} = \Omega_{i,j,r}[M_{1,r,t}, M_{2,r,t}, \dots]$

Regional Damage: $A_{j,r,t} = \Delta_{j,r}[Z_{1,j,r,t}, Z_{2,j,r,t}, \dots]$

Regional welfare weights

Discount factor

Regional instantaneous utility denominated over consumption of *j* individual commodities in *r* regions

Production is Where We Model Climate Damages Exerting Their Effects

Welfare: $\max \sum_r \sum_{t=\{0,\ldots,T\}} \phi_{r,t} \cdot \beta^t \cdot \mathcal{U}_r[C_{1,r,t}, C_{2,r,t}, \ldots]$

Sectoral Output: $Q_{j,r,t} = A_{j,r,t} \cdot \mathcal{F}_{j,r}[K_{j,r,t}, E_{j,r,t}]$

Absorption: $Q_{j,r,t} = C_{j,r,t} + I_{j,r} \ldots + \Pi[X_t] \cdot E_{j,r,t}$

Energ… : $X_{t+1} = \ldots \sum_r E_{j,r,s} + \ldots$

Capit… $K_{j,r} \ldots \psi_{j,r} \cdot \sum \ldots (1-\delta) K \ldots$

Carbon Cyc… $\mathcal{H}_\rho[\ldots$

Regional Cl… $\mathcal{M}_{\mu,r} \ldots$

Regional In… $\ldots_{j,r}[\ldots$

Regional D… $[Z_{1,j,r,t}, Z_{2,j,r,t}, \ldots]$

Region-by-sector instantaneous economic output

Productivity shock associated with contemporaneous region- and sector-specific climate damage. This is the key unknown.

Region-by-sector production function denominated over inputs of capital and carbon-energy

Disposition of Product Determines the Capacity Constraint of the Economy

Welfare: $\ldots \phi_{r,t} \cdot \beta^t \cdot \mathcal{U}_r[C_{1,r,t}, C_{2,r,t}, \ldots]$

Output: $Q_{j,r,t} = A_{j,r,t} \cdot \mathcal{F}_{j,r}[K_{j,r,t}, E_{j,r,t}]$

Absorption: $Q_{j,r,t} = C_{j,r,t} + I_{j,r,t} + \Pi[X_t] \cdot E_{j,r,t}$

Energy Extraction: $X \ldots \Sigma_j \Sigma_r E_{j,r,s} + X_t \ldots$

Capital Accum.: $K_{j,r,t+1} = \psi_{j,r} \cdot \Sigma_{i'} I_{\ldots} \ldots (1 - \ldots$

Carbon Cycle: $G_{\rho,t+1} \ldots$

Regional Climate: $M_{\mu,r,t} \ldots \ldots]$

Regional Impacts: $Z_{i,j,r,t} \ldots {}_{,t}, \ldots]$

Regional Damage: $A_{j,r,t} = \Delta_{j,r}[Z_{1,j,r,t}, Z_{2,j,r,t}, \ldots]$

Output of each sector

Consumption

Investment

Global carbon-energy supply curve, i.e., average/marginal cost of energy as function of global energy use

Region-by-sector carbon-energy use

Cumulative Carbon-Energy Extraction Drives Increase in Global Marginal Cost

Welfare: $\sum_r \sum_{t=\{0,\ldots,T\}} \phi_{r,t} \cdot \beta^t \cdot \mathcal{U}_r[C_{1,r,t}, C_{2,r,t}, \ldots]$

Sectoral: $Q_{j,r,t} = A_{j,r,t} \cdot \mathcal{F}_{j,r}[K_{j,r,t}, E_{j,r,t}]$

Absorption: $Q_{j,r,t} = C_{j,r,t} + I_{j,r,t} + \Pi[X_t] \cdot E_{j,r,t}$

Energy Extraction: $X_{t+1} = \sum_j \sum_r E_{j,r,t} + X_t$

Capital Accum.: $K_{j,r,t+1} = \ldots_{j,r} \cdot \sum_{j'} I_{j',r} \ldots + (1 - \delta) K_{j,r,t}$

Carbon Cycle:

Regional Climate:

Regional Impacts: $Z_{i,j,r,t} = \Omega_{i,j,r}[M_{1,r,t}, M_{2,r,t}, \ldots]$

Regional Damage: $A_{j,r,t} = \Delta_{j,r}[Z_{1,j,r,t}, Z_{2,j,r,t}, \ldots]$

Cumulative extraction of carbon-energy

Current energy use

Past history of extraction

(Endogenous) Accumulation of Capital is the Key Engine of Economic Growth

Welfare: $\max \sum_r \sum_{t=\{0,\ldots,T\}} \phi_{r,t} \cdot \beta^t \cdot \mathcal{U}_r[C_{1,r,t}, C_{2,r,t}, \ldots]$

Sectoral O…: $Q_{j,r,t} = A_{j,r,t} \cdot \mathcal{F}_{j,r}[K_{\ldots}, E_{\ldots}]$

Absorpt…: $Q_{j,r,t} = C_{j,r,t} + I_{j,r,t} + \ldots_{j,r,t}$

Energy Extraction: $X_{t+1} = \sum_j \sum_r E_{j,r,s} + X_t$

Capital Accum.: $K_{j,r,t+1} = \psi_{j,r} \cdot \sum_{j'} I_{j',r,t} + (1 - \delta)\, K_{j,r,t}$

Carbon Cycle: $G_{\rho,t+1} = \mathcal{H}[\sum_j \sum_r E_{j,r,t}, G_{\rho,t}]$

Regional Climate: … $G_{1,t}, G_{2,t}, \ldots$

Regional Impacts: … $M_{1,r,t}, M_{2,r,t}, \ldots$

Regional Damage: $A_{j,r,t} = \Delta_{j,r}[Z_{1,j,r,t}, Z_{2,j,r,t}, \ldots]$

New region- and sector-specific capital

Depreciation factor

Sectoral investment (sectors enjoy fixed shares of aggregate investment)

Extant region- and sector-specific capital

Carbon Cycle Model ($\mathcal{H}$) Translates GHG Emissions into Reservoir Concentrations

Welfare: $\max \sum_r \sum_{t=\{0,\ldots,T\}} \phi \ldots _{,r,t}, C_{2,r,t}, \ldots]$

S… $Q_{j,r,t} = A_{j,r,t} \cdot \ldots$

A… $Q_{j,r,t} = C_{j,r,t} + I_{j} \ldots + \mathcal{T}[X_t] \cdot E_{j,r,t}$

E…: $X_{t+1} = \sum_j \sum_r E_{j,r,s} \ldots X_t$

Capital Accum.: $K_{j,r,t+1} = \psi_{j,r} \cdot \sum_{j'} \ldots_{j',r,t} + (1 - \delta) K_{j,r,t}$

Carbon Cycle: $G_{\rho,t+1} = \mathcal{H}_{\rho}[\sum_j \sum_r E_{j,r,t}, G_{\rho,t}]$

Regional Climate: $M_{\mu,r,t} = \mathcal{M}_{\mu,r}[G_{1,t}, G_{2,t} \ldots]$

Regional Impacts: $Z_{i,j,r,t} = \Omega_{i,j,r}[M_{1,r,t}, M \ldots$

Regional Damage: $A_{j,r,t} = \Delta_{j,r}[Z_{1,j,r,t}, Z_{2,j,} \ldots$

New GHG concentrations by reservoir ρ (e.g., atmosphere, mixed-layer ocean, deep ocean) at global scale

Global emissions from use of carbon-energy

Extant GHG concentrations by reservoir

Climate Model ($\mathcal{M}$) Translates GHG Concentrations into Meteorology

Welfare: $\max \sum_r \sum_{t=\{0,\ldots,T\}} \phi_{r,t} \cdot \beta^t \cdot \mathcal{U}_r[C_{1,r,t}, C_{2,r,t}, \ldots]$

Sectoral Output: $Q_{j,r,t} = A_{j,r,t} \cdot \mathcal{F}_{j,r}[K_{j,r,t}, E_{j,r,t}]$

$Q_{j,r,t} = C_{j,r,t} + I_{j,r,t} + \Pi[X_t] \cdot E_{j,r,t}$

: $X_{t+1} = \sum_j \sum_r E_{j,r,s} + X_t$

$K_{j,r,t+1} = \psi_{j,r} \cdot \sum_{j'} I_{j',r,t}$

Carbon Cycle: $G_{\rho,t+1} = \mathcal{H}_\rho[\sum_j \sum_r E_{j,r,t}$ … $_{\rho,t}]$

Regional Climate: $M_{\mu,r,t} = \mathcal{M}_{\mu,r}[G_{1,t}, G_{2,t}, \ldots]$

Regional Impacts: $Z_{i,j,r,t} = \Omega_{i,j,r}[M_{1,r,t}, M_{2,r,t}, \ldots]$

Regional Damage: $A_{j,r,t} = \Delta_{j,r}[Z_{1,j,r,t}, Z_{2,j,r,t}, \ldots]$

> Meteorological variables (e.g., temperature, precipitation, sea levels) at regional scales

> Extant GHG concentrations by reservoir

Impacts Model (Ω) Translates Regional Meteorology into Physical Endpoints

Welfare: $\max \sum_r \sum_{t=\{0,\ldots,T\}} \phi_{r,t} \cdot \beta^t \cdot \mathcal{U}_r[C_{1,r,t}, C_{2,r,t}, \ldots]$

Sectoral Output: $Q_{j,r,t} = A_{j,r,t} \cdot \mathcal{F}_{j,r}[K_{j,r,t}, E_{j,r,t}]$

Absorption: $Q \ldots = C_{j,r,t} + I_{j,r,t} + \Pi[X_t] \cdot E_{j,r,t}$

Energy … $\sum_j \sum_r E_{j,r,\ldots}$

Capital … $= \psi_{j,r} \cdot \sum \ldots K_{j,r,t}$

Carbon … $_{t+1} = \mathcal{H}_\rho[\sum_j \sum_r \ldots, G_{\rho,t}]$

Regional Climate: $T_{\mu,r,t} = \mathcal{M}_{\mu,r}[G_{1,t}, \ldots_{2,t}, \ldots]$

Regional Impacts: $Z_{i,j,r,t} = \Omega_{i,j,r}[M_{1,r,t}, M_{2,r,t}, \ldots]$

Regional Damage: $A_{j,r,t} = \Delta_{j,r}[Z_{1,j,r,t}, Z_{2,j,r,t}, \ldots]$

Contemporaneous values of *i* physical impact endpoints by sector, region and time period

Regional values of meteorological variables

Damage Model (Δ) Translates Physical Impact Endpoints into Productivity Shocks

Welfare: $\max \sum_r \sum_{t=\{0,\ldots,T\}} \phi_{r,t} \cdot \beta^t \cdot \mathcal{U}_r[C_{1,r,t}, C_{2,r,t}, \ldots]$

Sectoral Output: $Q_{j,r,t} = A_{j,r,t} \cdot \mathcal{F}_{j,r}[K_{j,r,t}, E_{j,r,t}]$

Absorption: $Q_{j,r,t} = C_{j,r,t} + I_{j,r,t} + \Pi[X_t] \cdot E_{j,r,t}$

Energy Extraction: $X \ldots = \sum_j \sum_r E_{j,r,s} + X_t$

Capital … $= \psi_{j,r} \ldots) K_{j,r,t}$

Carbon … $= \mathcal{H}_\rho \ldots$

Regional Climate: $\ldots_{r,t} = \mathcal{M}_{\mu,r}[\ldots G_{2,t}, \ldots]$

Regional Impacts: $\ldots_{i,j,r,t} = \Omega_{i,j,r}[M_{1,r,t}, M_{2,r,t}, \ldots]$

Regional Damage: $A_{j,r,t} = \Delta_{j,r}[Z_{1,j,r,t}, Z_{2,j,r,t}, \ldots]$

Contemporaneous effect of climate damages on the productivity of individual sectors in each region

Distinct physical effects of climate change on a given sector

Key Points

- IAMs would be constructed so as to have sectoral as well as regional detail in production, consumption and climate damages
- Based on simulated climatic changes at the regional scale, we would first want to elaborate impacts by category of physical endpoint, sector, region and future time period
- Only then would we aggregate across endpoints to generate sector-by-region trajectories of shocks
- No aggregate damage function per se, so transparent causal chain from both ex ante shocks (A) and ex-post adjustments in regional/sectoral output and consumption (i.e., reactive adaptation) to ultimate welfare effects

Implications: The Marginal External Cost of Carbon

- Climate impacts of an additional unit of carbon energy use at $t = 0$, cumulated over future periods:

Marginal utility of consumption of output of affected sector

potential output by region/sector

Marginal effects of impact endpoints on productivity of sectors in each region

$$\sum_r \sum_{t=\{0,\ldots,T\}} \phi_{r,t} \beta^t \sum_j \langle \partial \mathcal{U}_r / \partial C_{j,r,t} \times \mathcal{F}_{j,r,t} \times \sum_i \{ \partial \Delta_{j,r} / \partial Z_{i,j,r,t}$$

$$\times \sum_\mu [\partial \Omega_{i,j,r} / \partial M_{\mu,r,t} \times \sum_\rho (\partial \mathcal{M}_{\mu,t} / \partial G_{\rho,t} \times \partial \mathcal{H}_\rho / \partial E_0)]\}\rangle$$

Marginal effects of meteorological variables on physical impact endpoints, disaggregated by region/sector

Marginal effects of reservoir GHG concentrations on meteorology at regional scales

Marginal effect of emissions on the global carbon cycle

A Critical Review of the State of Current Practice

The Damage Function Approach (Nordhaus)

- Based on exogenous global-scale climate change projections, elaborate impacts (some denominated by category of physical endpoint, some by sector) by region for a benchmark global mean temperature change (2.5°C)
- Monetize, aggregate and express the resulting estimates as a proportion of future potential GDP
- Use assumptions about how proportion will scale with (a) income and (b) a simplified index of the magnitude of climate change (global mean temperature change, $\mathcal{T}$) to specify aggregate damage function ($\mathcal{D}$)
- Some baby steps toward the sector/impact category disaggregation of the canonical model: sea-level rise in RICE-2010

The Marginal External Cost of Carbon as Calculated in RICE

Marginal utility of aggregate regional consumption

Potential regional GDP

Marginal effect of temperature on aggregate output in each region

$$\sum_r \sum_{t=\{0,\ldots,T\}} \phi_{r,t} \beta^t \partial \mathcal{U}_r / \partial C_{r,t} \times \mathcal{F}_{r,t} \times \partial \mathcal{D}_r / \partial \mathcal{T}_t$$

$$\times \sum_\rho \left(\partial \mathcal{T}_t / \partial G_{\rho,t} \times \partial \mathcal{H}_\rho / \partial E_0 \right)$$

Marginal effects of reservoir GHG concentrations on global mean temperature change

Marginal effect of emissions on the global carbon cycle

Difficult Problems, with Elusive Remedies

- Aggregation is inevitable, but on the modeling side, the key research need is to explicitly incorporate sectoral detail (*j*), impact categories (*i*) in IAMs
- Major obstacle: lack of empirical or detailed modeling studies; most of existing ones don't go past 2050 (cf. World Bank, 2010; Eboli et al., 2009)
- Targeting later decades for quasi-empirical assessment is critical, as 2050 likely to underestimate the onset of warming and climate damages late in the century
- But the further one goes out in time the less confidence one has in detailed estimates, leading to tradeoff between overall response magnitude and sectoral/regional specificity
- No easy way to cut this Gordian knot

CGE Models for Climate Impact Analysis

- Promising new direction, particularly given increasing climate model skill at regional scales
- An explicitly multi-regional/multi-sectoral approach: compute shocks based on exogenous information on physical endpoints by sector, impose consequent shocks on affected sectors within the various regions
- Key problems are CGE models' recursive-dynamic character (which precludes anticipation of impacts), limited time horizon (2050 in ICES)

Adaptation and Technological Change

Karen Fisher-Vanden, Elisa Lanzi, David Popp, Ian Sue Wing, Mort Webster

The purpose of this talk is to provide a brief summary of the state of the science on the influences of adaptation on the social cost of climate change. Specifically, the charge was to discuss (not necessarily in this order):

(1) relevant studies on the observed or potential effectiveness of adaptive measures, and on private behaviors and public projects regarding adaptation;
(2) relevant studies on how to forecast adaptive capacity;
(3) how adaptation and technical change could be represented in an IAM (for at least one illustrative sector);
(4) whether the information required to calibrate such a model is currently available, and, if not, what new research is needed; and
(5) how well or poorly existing IAMs incorporate the existing body of evidence on adaptation.

A tall order, but important to get our arms around since estimates of the net impact of climate change could be significantly higher if adaptation is not taken into account.[1]

As elaborated below, a number of general insights have resulted from our brief foray into this topic that have implications for the development of a future research program in this area. First, modeling adaptation is inherently difficult given the nature of the adaptation process, requiring advancements in modeling techniques. Second, although there has been good empirical work done on impacts and adaptation costs, the coverage is limited requiring heroic efforts to translate the results into model parameters. More work is needed to bridge the gap between models and empirical studies. Lastly, adaptation-related technological change is generally lacking in current models but could significant lower adaptation cost estimates. This stems from a general lack of understanding of the process related to this type of technological change. More empirical work is needed in this area.

What is unique about the adaptation process that justifies the need to add features to existing integrated assessment models (IAMs)? First, adaptation is in response to current or anticipated impacts and comes in different forms: (a) reactive (e.g., changes in heating/cooling expenditures; treatment of disease; shifts in production); and (b) proactive (e.g., infrastructure construction (e.g., seawalls); early warning systems; water supply protection investments. In some IAMs adaptation would occur endogenously in reaction to changes in prices due to climate impacts—e.g., more power plants built to deal with increases in demand for air conditioning; shifts in production in reaction to higher prices of factors negatively impacted by climate change. However, many adaptation activities that would occur in reality, such as investment in flood protection, would not occur in a simulated model unless there is explicit representation of climate damages to induce reactive expenditures and proactive investments.

Second, unlike mitigation investments where investments today result in reductions today, proactive adaptation investments are made today to provide protection against possible future impacts. Thus, adaptation investment decisions are inherently intertemporal and therefore

[1] For the U.S., Mendelsohn et al. (1994) estimates that the net impact of climate change on the farming sector will be 70% less if adaptation is included while Yohe et al. (1996) estimates that the net impact on coasts will be approximately 90% less (Mendelsohn (2000)).

models need to include intertemporal decision making for proactive adaptation investments, in order to trade off future damages and current adaptation investment expenditures. Not only are we making intertemporal adaptation decisions, we are specifically making proactive adaptation investments under uncertainty. Whether we invest and how much to invest all depends on our expectations regarding future impacts and how we value the future. Therefore, we need a model that allows for intertemporal decision-making under uncertainty.

Climate damages and adaptation strategies are locally- or regionally-based. Therefore, ideally the model will include regional detail or will apply a method to aggregate up to a more coarse regional representation. Climate damages and adaptation expenditures are also sector specific—e.g., certain sectors will be impacted more than others and adaptation expenditures will be directed at specific sectors (e.g., electric power, construction). Thus, a model with sectoral detail or a way to aggregate these sector-specific impacts and expenditures is desirable.

The demand for adaptation solutions will induce adaptation-related technological change. Do inducements for adaptation-related technological change differ markedly from mitigation-related technological change, requiring a different modeling approach? To the extent that adaptation activities may be region or sector specific, markets for new adaptation techniques will be smaller than for new mitigation techniques, making private sector R&D investments less attractive. Given this, as well as the case that adaptation investments are largely public infrastructure investments, distinguishing between public R&D and private R&D may be important. Note that this is more than a question of simply basic versus applied science, but driven by the nature of demand for the final product, much in the same way that the government finances most R&D for national defense. Thus, the model needs to be capable of distinguishing between private and public investments and include mechanisms of public revenue raising to fund these projects.

To summarize, to be able to capture adaptation strategies, an ideal IAM would include the following features:

- Explicit modeling of climate damages/impacts
- Intertemporal decision making under uncertainty
- Endogenous technological change
- Regional and sectoral detail for impacts and adaptation strategies
- Connection with empirical work on impacts and adaptation

Is it feasible or even desirable to have all of these features represented in a single model, since transparency is lost as more features are added? It is important to measure the trade-offs:

- How much of this needs to be specifically represented in the model and how could be represented outside of the model
- To cite Jake Jacoby: "different horses for different courses." Do we need a suite of models each designed to capture a subset of these features?
- How important is each of these features to the social cost of climate change? Sensitivity analysis could be useful here to assess whether we even need to worry about including certain features.

To answer these questions, it is useful to first survey what features currently exist in IAMs. A number of modeling approaches have been taken to capture impacts and adaptation. Computable general equilibrium (CGE) models have the advantage of providing sectoral and regional detail and capturing the indirect effects of impacts and adaptation. Thus, given its structure, CGE models can more easily accommodate regional and sectoral-specific damage functions. Most CGE models, however, do not include the type of intertemporal decision making required to model proactive adaptation investment decisions, given the computational demands required by a model with detailed regions and sectors. However, there have been a number of CGE models that have been used to estimate the cost of climate change impacts; for example,

- DART (Deke et al, 2001)—to study the cost of coastal protection
- FARM (Darwin and Tol, 2001; Darwin et al, 1995)—includes detailed land types to study the effects of sea level rise and impacts of climate change on agriculture.
- GTAP-E/GTAP-EF (Bosello et al, 2006; Bigano et al, 2008; Rosen, 2003)—has been used to study induced demand for coastal protection; effects of rising temperatures on energy demand (Bosello et al, 2007); health effects of climate change (Bosello et al, 2006); effects of climate change on tourism. Focuses on one impact at a time.
- Hamburg Tourism Model (HTM) (Berittella et al, 2006; Bigano et al, 2008)—used to study the effect of climate change on tourism.
- ICES (Eboli et al, 2010)—models multiple impacts simultaneously: impacts on agriculture, energy demand, human health, tourism, and sea level rise.

Another set of models used to study climate change impacts and adaptation fall under the category of optimal growth models. These models include intertemporal optimization but typically lack sectoral and regional detail given the computational demands this would require. These include:

- DICE/RICE (Nordhaus, 1994; Nordhaus and Yang, 1996; Nordhaus and Boyer, 2000)—DICE comprises one region, one aggregate economy, and one damage function aggregating many impacts. RICE comprises 13 regions, each with its own production function and damage function.
- AD-DICE/AD-RICE (de Bruin et al, 2009)—DICE/RICE model with adaptation. Adaptation investment added as a decision variable which lowers damages and faces an adaptation cost curve. Residual damages are separated from protection costs in the damage function.

There are also a number of simulation models that have been developed to study the effects of climate change impacts. The major difference from CGE and optimal growth models is that simulation models do not optimize an objective function, such as intertemporal utility. Instead, these models represent a number of interconnected relationships that allow for studying the propagation of perturbations to the system. Two widely used simulation models are:

- PAGE (Plambeck and Hope, 1997; Hope, 2006)—PAGE comprises eight regions each with its own damage functions for two impact sectors (economic and non-economic). The authors use information on impacts from IPCC (2001) to generate model parameter values related to impacts. In addition, PAGE stochastically models catastrophic events where the probability of an event increases when temperature exceeds a certain threshold. Simple adaptation is included in the model which reduces damages. Assumes developed countries can reduce up to 90% of economic impacts while developing can reduce up to 50%. All regions can reduce up to 25% of non-economic impacts.

- FUND (Tol et al, 1995; Tol, 1995)—referred to as a "policy optimization" model. Exogenous variables include population (from the World Bank), GDP per capita (from EMF 14), and energy use. Endogenous variables include atmospheric concentrations, radiative forcing, climate impacts (species loss, agriculture, coastal protection, life loss, tropical cyclones, immigration, emigration, wetland, dryland), emission reductions (energy or carbon efficiency improvements, forestry measures, lower economic output), ancillary benefits (e.g., improved air quality), and afforestation. The model comprises 9 regions with game theoretics and eight market and non-market sectors, each with its own calibrated damage function. Adaptation is modeled explicitly in the agricultural and coastal sectors, and implicitly in other sectors such as energy and human health where the wealthy are assumed to be less vulnerable to the impacts of climate change. No optimization in the base case—just simulation. In the optimization case, the model is choosing the optimal level of emissions reductions by trading off costs and benefits of reductions.

Another class of models involves hybrid combinations of the above model types. For example,

- Bosello and Zhang (2006) couple an optimal growth model with the GTAP-E model of Burniaux and Truong (2002) to study the effects of climate change on agriculture
- Bosello et al (2010) couple the ICES CGE model with an optimal growth model (AD-WITCH) to study adaptation to climate change impacts.
- AD-WITCH (Bosello et al, 2010)—an optimal growth model with detailed bottom-up representation of the energy sector. Comprises 12 regions where the following seven control variables exist for each region: investment in physical capital, investment in R&D, investment in energy technologies, consumption of fossil fuels, investment in proactive adaptation, investment in adaptation knowledge; and reactive adaptation expenditure. These alternative uses of regional income compete with each other.

To parameterize these models, most modeling teams look to empirical studies of impacts and adaptation and are faced with similar frustrations. First, as elaborated in Agrawala and Fankhauser (2008), the empirical work in the area of adaptation is severely lacking. The authors find that although information exists on adaptation costs at the sector level, certain sectors (e.g., coastal zones and agriculture) are studied more heavily than others. Second, most empirical studies are not done with modeling applications in mind. Most modelers find themselves forced to devise methods to scale up from the regional and sectoral results generated by empirical studies.

There have been a few recent studies that have attempted to summarize the empirical work on adaptation costs; e.g.,

- Agrawala and Fankhauser (2008)—provides a critical analysis of empirical work on adaptation costs. Tables summarize empirical sectoral studies on adaptation costs. Sectors include coastal zones, agriculture, water resources, energy demand, infrastructure, tourism and public health.
- World Bank (2010)—report from The Economics of Adaptation to Climate Change (EACC) study. Seven sector-specific studies: infrastructure, coastal zones, water supply and flood protection, agriculture, fisheries, human health, extreme weather events. Provides detailed estimates of adaptation costs; some generated using dose response functions with engineering estimates and some generated from sector-specific models.
- UNFCCC (2007)—regional studies (Africa, Asia, Latin America, and small island developing States) on vulnerability; current adaptation plans/strategies; future adaptation plans/strategies. Most information from national communications to the UNFCCC, regional workshops, and expert meetings.

A few modeling teams have made serious attempts to integrate existing empirical work on adaptation into their model; for example,

- AD-DICE/AD-RICE: starts with damage functions of Nordhaus and Boyer (2000) and uses empirical studies to separate residual damages from adaptation costs. Various studies on adaptation measures for certain sectors (i.e., agriculture and health) and estimates of adaptation costs from existing studies are used. Also, other model results—e.g., results from FUND—are used to estimate adaptation costs in response to sea level rise. Empirical studies to separate residual damages from adaptation costs are not available for many of the sectors—i.e., other vulnerable markets; non-market time use; catastrophic risks; settlements—so assumptions were made in order to separate the damage costs. However, these sectoral estimates are ultimately aggregated up to one damage cost number and one adaptation cost number to fit with the one sector structure of the model.
- AD-WITCH: Uses empirical information from the construction of damage functions in Nordhaus and Boyer (2000), the studies in Agrawala and Fankhauser (2008); and UNFCCC (2007) to separate residual damages from adaptation costs. Similar to AD-DICE, using these empirical studies to separate the damage estimates in Nordhaus and Boyer (2000) into residual damages and adaptation costs.

Comparing this brief survey of existing work in this area with the list of required modeling features needed to model adaptation, a couple of key research voids stand out. First, none of these models include decision making under uncertainty, and for good reason. It is difficult to do. Optimal growth models like DICE with intertemporal decision making are deterministic and fully forward-looking. Past approaches to modify such a model to be stochastic usually entail the following steps:

1) Create multiple States of the World (SOWs), each with different parameter assumptions and different probabilities of occurrence;
2) Index all variables and equations in the model by SOW;
3) Add constraints to the decision variables so that for all time periods before information is revealed, decisions must be equal across SOWs.

The problem with this approach is that it rapidly becomes a very large constrained nonlinear programming problem, and often the model will not converge to a solution for more than a trivial number of SOWs. The general problem of decision making under uncertainty is a stochastic dynamic programming problem that requires the exploration of a large number of samples of outcomes in every time period. The challenge is to fully explore the sample space while keeping the model computationally tractable. Promising on-going research by Mort Webster and his team at MIT could offer an alternative approach to modeling decision making under uncertainty. Webster's NSF-funded project team is currently developing a formulation based a new approach called Approximate Dynamic Programming, introduced by Powell (2007) and others. This approach implements dynamic programming models by iteratively sampling the state space using Monte Carlo techniques, approximating the value function from those samples, and using approximate value functions to solve for an approximate optimal policy, then repeating. This approach has been used successfully in other contexts for very large state spaces. Mort Webster's team is currently developing an ADP version of the ENTICE-BR model to study R&D decision making under uncertainty.

Second, adaptation-related technological change is largely absent in current models. Most models are calibrated using existing knowledge of adaptation strategies and costs with no allowance for improvements in these strategies and technologies. AD-WITCH (Bosello et al, 2009) does attempt to account for this by including investment in adaptation knowledge as a decision variable that competes with other types of investment. Investments in adaptation knowledge accumulate as a stock which reduces the negative impact of climate change on gross output. However, the lack of empirical studies on adaptation-related technological change limits the modelers' ability to calibrate their model based on empirical knowledge. In the case of AD-WITCH, adaptation knowledge investments only relate to R&D expenditures in the health care sector where empirical data exist. This suggests that more empirical research in this area is desperately needed.

Third, differences in adaptive capacity or differences in the ability of regions to adapt to climate change are also important to capture in model analyses given the implications for distributional effects but are typically not represented in existing models. The FUND model implicitly captures adaptive capacity in the energy and health sectors by assuming wealthier nations are less vulnerable to climate impacts. However, it seems that only one model, AD-WITCH, attempts to explicitly capture adaptive capacity through the inclusion of investments in adaptation knowledge as a decision variable. Not only does this variable capture R&D investments in adaptation-related technologies as discussed in the previous paragraph, it also captures expenditures to improve the region's ability to adapt to climate change. Issues arise, however, when the model is calibrated since the modelers were only able to identify one source of qualitative information on adaptive capacity (i.e., the UNFCCC (2007) report discussed above) which only covers four aggregate regions (Africa, Asia, small island developing States, and Latin America). Assumptions were then made to translate this information to the regional representation and model parameters in AD-WITCH.

Lastly, another area where empirical work to inform models is lacking is in the dynamics of recovery from climate change impacts. Most models represent climate damages as a reduction in economic output which is assumed to recover over time. Empirical work on thresholds and time to recover including factors that influence these variables could help inform models on the type of dynamics that should be captured in impact and adaptation analyses. Also, better techniques to translate results from empirical studies to models are needed since the sectoral and regional detail of empirical studies does not typically align with the sectoral and regional detail in models. In general, to address the disconnect between empirical studies and modeling needs, we as a research community need to devise better ways to facilitate communication between empirical researchers and modelers.

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Adaptation and Technological Change

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Purpose of the talk

Charge: To provide a summary of the state of the science on the influences of adaptation on the social cost of climate change; specifically, discuss

(1) relevant studies on the observed or potential effectiveness of adaptive measures, and on private behaviors and public projects regarding adaptation;

(2) relevant studies on how to forecast adaptive capacity;

(3) how adaptation and technical change could be represented in an IAM (for at least one illustrative sector);

(4) whether the information required to calibrate such a model is currently available, and, if not, what new research is needed; and

(5) how well or poorly existing IAMs incorporate the existing body of evidence on adaptation

General conclusions

- Modeling adaptation is inherently difficult. Requires advancements in modeling techniques
- Coverage of empirical work on adaptation limited. Requires heroic efforts to bring into IAMs. Need to bridge gap between models and empirical studies.
- Adaptation-related technological change is lacking in current IAMs. More empirical work is needed in this area to inform existing models.

What is unique about the adaptation process?

1. Adaptation is in response to current or anticipated impacts. Comes in two forms:

    - Reactive—e.g., changes in heating/cooling expenditures; treatment of disease; shifts in production
    - Proactive—e.g., infrastructure construction (seawalls); early warning systems; water supply protection investments

Need explicit representation of climate damages to induce reactive expenditures and proactive investment.

What is unique about the adaptation process?

2. Proactive adaptation investment decisions made today to provide possible future protection; decisions are therefore

   - Inherently intertemporal
   - Made under uncertainty

Need model that can allows for intertemporal decision-making under uncertainty.

What is unique about the adaptation process?

3. Is adaptation-related technological change markedly different from mitigation-related technological change?

   - Public R&D versus private R&D?
   - Inducements different?

Need model capable of distinguishing between these two types of technological change.

What is unique about the adaptation process?

4. Impacts and adaptation responses are locally- or regionally-based. Adaptation expenditures are sector-specific.

Therefore, need model that includes

- regional detail
- sectoral detail
- method to aggregate to more coarse representation

Important model features for adaptation

- Explicit modeling of climate damages/impacts
- Intertemporal decision making under uncertainty
- Endogenous adaptation-related technological change
- Regional and sectoral detail
- Connection with empirical work on impacts and adaptation

Model	Impacts	Regional detail	Sectoral detail	Link to empirical work on adaptation	Intertemporal?	Uncertainty	Adaptation
AD-WITCH	Region-specific climate damage functions	12 regions	Bottom-up energy sector (7)	To separate adaptation costs and residual damages	Optimal growth-Perfect foresight	Application where uncertain R&D modeled implicitly	Investment in proactive, reactive, and knowledge adaptation
AD-DICE/AD-RICE	Region-specific climate damage functions (AD-RICE)	13 regions (AD-RICE)	One aggregate economy for each region	Similar to AD-WITCH	Optimal growth-Perfect foresight		Adaptation investment included as decision variable
PAGE	Region-specific damage functions for two sectors (economic and noneconomic)	8 regions	One economic sector for each region	IPCC TAR?	Simulation model	Stochastically models catastrophic events	Simple adaptation included which increases tolerable level
FUND	Damage function for each of 8 sectors	9 regions	8 market and non-market sectors	Limited	Simulation model	Application with monte carlo simulation	Explicit in ag and coastal sectors; implicit in energy and human health
GTAP-E/GTAP-EF	Used for separate impact studies	8 regions	CGE-8 or 17 sectors	Limited	Static		
ICES	Models 5 impacts simultaneously	8 regions	CGE-17 sectors		Dynamic recursive		
FARM	Sea level rise and impacts on agric	12 regions—detailed land types	CGE-13 sectors	Limited	Static		Coastal protection

Empirical studies on adaptation

- Agrawala and Fankhauser (2008)—OECD publication which summarizes empirical work on adaptations costs.
  - Sectors include: coastal zones; agriculture; water resources; energy demand; infrastructure; tourism; and public health.

- World Bank (2010)—report from the Economics of Adaptation to Climate Change (EACC) research program at WB
  - Seven sector-specific studies on adaptation costs: infrastructure; coastal zones; water supply and flood protection; agriculture; fisheries; human health; extreme weather events

- UNFCCC (2007)—Four regional (Africa, Asia, Latin America, and small island developing States) studies on vulnerability, and current and future adaptation plans/strategies.
  - Information from UNFCCC National Communications, regional workshops, and expert meetings.

Recommended future research areas—Decision making under uncertainty

- Past approaches involve:
  1. Create multiple States of the World (SOWs)
  2. Index all variables and equations in model by SOW.
  3. Solve by constraining decision variable to have single value across SOWs in all time periods before information is known.

- Problem with this approach: Rapidly becomes intractable for more than a few SOWs.

- New research by Mort Webster (MIT) applying Approximate Dynamic Programming introduced by Powell (2007):
  1. Sample state space using Monte Carlo techniques
  2. Approximate value function from these samples
  3. Solve for approximate optimal policy using these approximate value functions

Recommended future research areas—Adaptation-related technological change

- Adaptation-related technological change largely absent in current models
- Most models calibrated based on current adaptation cost estimates. No allowance for technological improvements.
  - Exception: AD-WITCH includes investment in adaptation knowledge which lowers future cost of adaptation. Only applied to health care sector.
- Lack of empirical studies limits modeler's ability to represent adaptation-related technological change in current models
- More empirical work in this area is desperately needed

Recommended future research areas—Empirical work on adaptive capacity

- Regional differences in adaptive capacity important to capture in models. Will affect distributional effects of climate impacts

- Largely absent in existing models
  - Exceptions:
    - FUND model assumes wealthier nations less vulnerable to climate impacts in the energy and health sectors.
    - AD-WITCH's investment in adaptation knowledge also captures expenditures to improve region's ability to adapt

- Although in both cases, modelers were limited by lack of empirical data. UNFCCC (2007) provides adaptive capacity measure but only for four aggregate regions.

- Heroic efforts required to translate this little empirical information to model parameters

Recommended future research areas—Dynamics of recovery

- Lack of empirical evidence on the dynamics of recovery from climate change impacts.

  E.g., time to recovery, thresholds and factors affecting these variables

- Important for model calibration

- In general, need techniques to better translate results from empirical studies to models; e.g.,
  - Regional and sectoral detail do not typically align

*** Going forward, we need to devise better ways to facilitate communication between empirical researchers and modelers.

Questions?/Discussion?

Multi-century scenario development and socioeconomic uncertainty

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Introduction

The social cost of carbon (SCC) sums the damages resulting from a unit emission of CO2 today over the infinite future. As a result, this quantity depends in principle on socio-economic and climate conditions over all future time. In practice, SCC calculations are truncated over a finite period, and different factors can change the relevance of damages that occur in the very long term. On the one hand, future damages are discounted, which makes damages far in the future contribute less to the net present value than those that occur in the nearer term. On the other hand, assumed growth in the size of the economy and damages that increase in proportional terms with the amount of warming will tend to increase the contribution of damages far in the future relative to those in the nearer term. Thus the contribution of damages that occur beyond 2100 – and therefore the importance of socio-economic conditions beyond 2100 – to the net present value of damages from a current emission are ambiguous. The contribution of long-term damages to the specific calculations carried out in the Interagency Working Group report on the social cost of carbon (IAWGSCC, 2010; hereafter the "SCC report") are not specified, so it is unclear how important long-term socio-economic assumptions are to these calculations. For the present purposes we assume they are relevant, at least in some scenarios. Since the SCC calculations in the report are carried out to the year 2300, I focus on socio-economic futures over this time period.

The scenario variables for which long-term assumptions are made in the SCC report include population, GDP, CO2 emissions, and non-CO2 forcing. I focus on the first three, and compare the assumptions made in the report to those available in the literature, for both the 2000-2100 and 2100-2300 time periods. The quantitative scenarios used in the report are based on a set of scenarios drawn from EMF-22, a recent model comparison exercise carried out by the Energy Modeling Forum. The report describes the five scenarios it selected as follows: "EMF BAU scenarios represent the modelers' judgment of the most likely pathway absent mitigation policies to reduce greenhouse gas emissions, rather than the wider range of possible outcomes. Nevertheless, these views of the most likely outcome span a wide range" (IAWGSCC, 2010, p. 16). It is worth noting, however, that typical practice in EMF exercises is not necessarily to use the most likely socio-economic futures, but rather those that are well suited to the particular exercise, or most convenient. There is no guarantee that their likelihood has been judged in any way. In addition, there is no guarantee that they span the range of uncertainty in the literature, and as we will see in the comparison, they typically do not.

Population

The SCC report's population scenarios, based on the EMF scenarios, span a range of 8.7-10.4 billion people globally by 2100. In comparison, the most recent long-term projections from the United Nations (UN, 2004) and the International Institute for Applied Systems Analysis (IIASA, Lutz, 2008) span ranges of 5.5 – 14 billion and 4.5 – 12 billion, respectively. Ranges of population assumptions employed in emissions scenarios contained in the AR4 scenario database are similarly wide (although cover the low end of this range less well). Thus, the SCC report clearly spans an overly narrow range of population assumptions in 2100, and can be characterized as essentially clustering around a single medium population assumption.

The report extends the projections to 2300 by assuming growth rates in 2100 linearly decline to zero, producing a global population size in 2300 of 8-10.9 billion. Both the UN (UN 2003) and IIASA (Lutz and Scherbov, 2008) have carried out illustrative long-term projections to 2300. In neither case do these institutions identify a most likely long-term outcome; rather, both emphasize that the projections are intended to be illustrative of the consequences of different assumptions about fertility and mortality. The UN produces three projections that differ only in terms of fertility rates, which are assumed to converge to levels between 1.85 and 2.35 births per woman in the long term. This relative narrow fertility range produces a range of global population size of 2.3 – 36.4 billion people in 2300. IIASA considers uncertainty in both fertility and mortality, and assumes that fertility converges to levels between 1.0 and 2.5 births per woman, based on various lines of reasoning regarding determinants of fertility behavior. These assumptions produce a range of global population size of between 40 million and 47 billion people in 2300. Thus the SCC report essentially does not consider uncertainty in long term population size at all, since the range of outcomes it considers vary by a factor of 1.4 between low and high projections, while those in the demographic literature vary by a factor of more than 1000.

It is also worth noting that other dimensions of population beyond total size are likely important for impacts and damages, including age structure. In the IIASA projections, by 2300 age structures vary widely as well. The proportion of the population aged 80+ increases from a few percent at present to between 20% and 65% by 2300, indicating a completely unprecedented demographic structure.

GDP

The global GDP scenarios adopted in the SCC report, based on EMF models, range from a global economy of $268-$397 trillion (in 2005 US $). In comparison, the scenarios in the AR4 database range from $136 – $677 trillion, a range spanning a factor of 5 versus the range of a factor of 1.5 assumed in the SCC report.

Beyond 2100 it is difficult to put the SCC assumptions in perspective given the dearth of long-term GDP scenarios in the literature. The SCC approach is to assume that growth rates of global GDP decline linearly to reach zero in 2300, based on the idea that "increasing scarcity of natural resources and the degradation of environmental sinks available for assimilating pollution from economic production activities may eventually overtake the rate of technological progress". While this is a plausible assumption, it is only one of many possible scenarios, and leads to a range of about $750 - $2200 trillion by 2300.

In contrast, an illustrative exercise by Tonneson (2008) applies a range of different growth rates to current GDP to project growth over the next 300 years. The growth rates are based on data for GDP per capita over the past 180 years, defining three scenarios by selecting the slowest and fastest periods of growth over this time span as well as the overall average growth rate. I combine these per capita growth rates with the projected population growth from the UN and IIASA scenarios, and with current estimated per capita GDP, to produce illustrative long-range GDP projections. They span a range in 2300 from around $100 trillion to around $1 million trillion – a range of a factor of 1000, far wider than the range of a factor of 3 covered by the SCC scenarios.

CO2 emissions

The range of CO2 emissions assumed in the SCC report result in emissions of 13-81 GtCO2/yr. The AR4 database includes emissions scenarios that range from -14 to 109 GtCO2/yr, which is somewhat larger but of the same order of magnitude as the SCC range.

Beyond 2100, the report assumes that rates of decline in the carbon intensity of GDP are maintained through 2300. This is based on the assumption that “technological improvements and innovations in the areas of energy efficiency and other carbon reducing technologies … will continue to proceed at roughly the same pace that is projected to occur towards the end of the forecast period”. As in the GDP case, this is a plausible assumption but only one of many possibilities. It produces a range of emissions in 2300 of about 10 to 102 GtCO2/yr. In the scenario literature, scenarios for emissions beyond 2100 that are based on socio-economic assumptions (rather than simple extrapolations) are scarce. A point of comparison, however, is provided by the emissions underlying the Representative Concentration Pathways (RCPs), which are concentration and forcing scenarios that are providing the basis for climate modeling simulations for the IPCC Fifth Assessment Report (Moss et al., 2010). The RCPs cover a similar range of emissions as the SCC report through 2100, and then decline to low levels by 2300 (less than 10 GtCO2/yr), so the SCC report covers a wider – and higher – range of emissions outcomes than will be assumed in climate model simulations for AR5.

Discussion and conclusions

In summary, the comparisons carried out here show that the assumptions regarding population and GDP pathways in the SCC report cover an overly narrow range of uncertainty over the entire time horizon, but especially in the long term (beyond 2100). In contrast, the range of emissions pathways through 2100 is reasonably consistent with the range found in the literature. Beyond 2100 the emissions range is wider and higher than the range found in the RCP extensions, although the RCP pathways were not designed to reflect uncertainty in very long term emissions. The comparison is instructive however in that the global average temperature projected from the RCPs reaches 8 degrees or more by 2300, and therefore the SCC pathways will result in temperature increases even higher than this.

There are several caveats to these conclusions that must be kept in mind. First, uncertainty ranges in literature may themselves be too conservative. While the very long term population projections in the literature have been constructed with an eye toward bounding assumptions that are reasonably well grounded, the long term GDP projections were constructed in a back of the envelope style that may underestimate actual uncertainty, and for CO2 emissions no similar exercise was found in the literature at all. Second, we have only examined uncertainty in very aggregate socio-economic variables such as global population size and global GDP, but future impacts will depend perhaps more strongly on additional dimensions of these variables, such as the regional and spatial distribution of people and production, and the sectoral composition of production. It is difficult to interpret what particular levels of GDP per capita in the long term even mean: what types of economic activities, relying on what types of technologies, might be taking place 300 years in the future, and how will this affect impacts? Do current damage functions apply even approximately to the socio-economic conditions that would obtain in the very long term? Finally, we have ignored the potential for catastrophic impacts and their implications for socio-economic conditions, despite the fact that some SCC emissions pathways could lead to more than 8 degrees C in warming over this time period.

Based on these conclusions, and taking into account these caveats, we make the following recommendations for future versions of the SCC report:

1. Demonstrate the influence of key sources of uncertainty on SCC calculations, including the contribution to the SCC from different time periods.
2. Drop the use of a range of best estimates as a characterization of uncertainty, which under-estimates uncertainty, and consider a substantially wider range of socio-economic futures, through 2100 and 2300.
3. Consider simpler approaches to calculating damages in the very long term, when uncertainty is highest, such as the use of generic economic sectors and damage types
4. Improve the characterization of uncertainty in SCC results and reconsider the use of probabilistic outcomes, since the probabilities reflect uncertainty in only some parts of the calculation and are highly conditional on assumption regarding other components, such as the socio-economic pathways.
5. Consider linking to evolving work on RCPs and socio-economic scenarios that are consistent with them.

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Multi-century scenario development and socioeconomic uncertainty

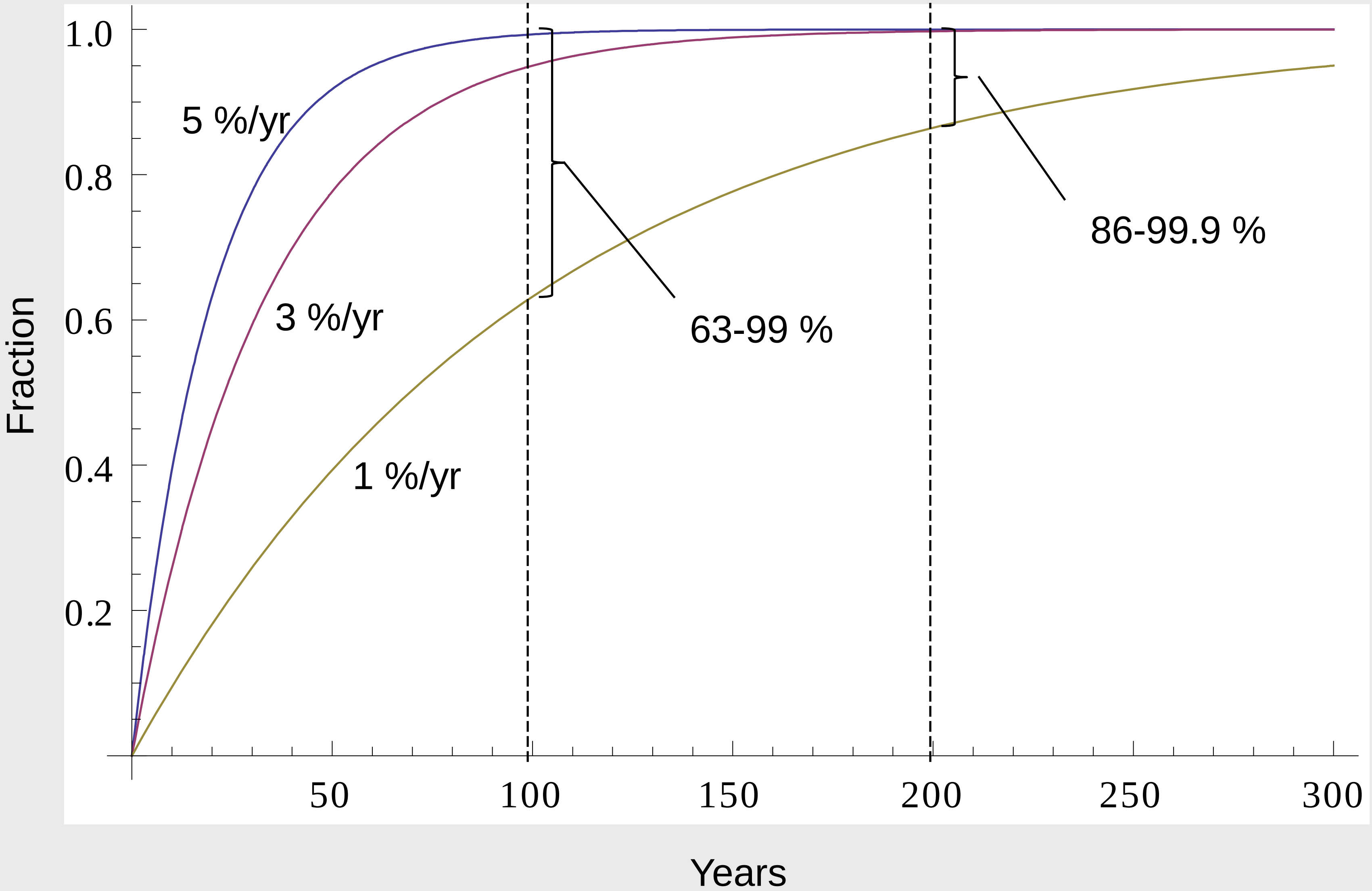
Brian O'Neill

National Center for Atmospheric Research (NCAR)

Workshop on Modeling Climate Change Impacts and Associated Economic Damages
EPA-DOE, Washington, DC, Nov 18-19, 2010

NCAR is sponsored by the National Science Foundation

Does the long term matter?



Scenario variables and SCC approach

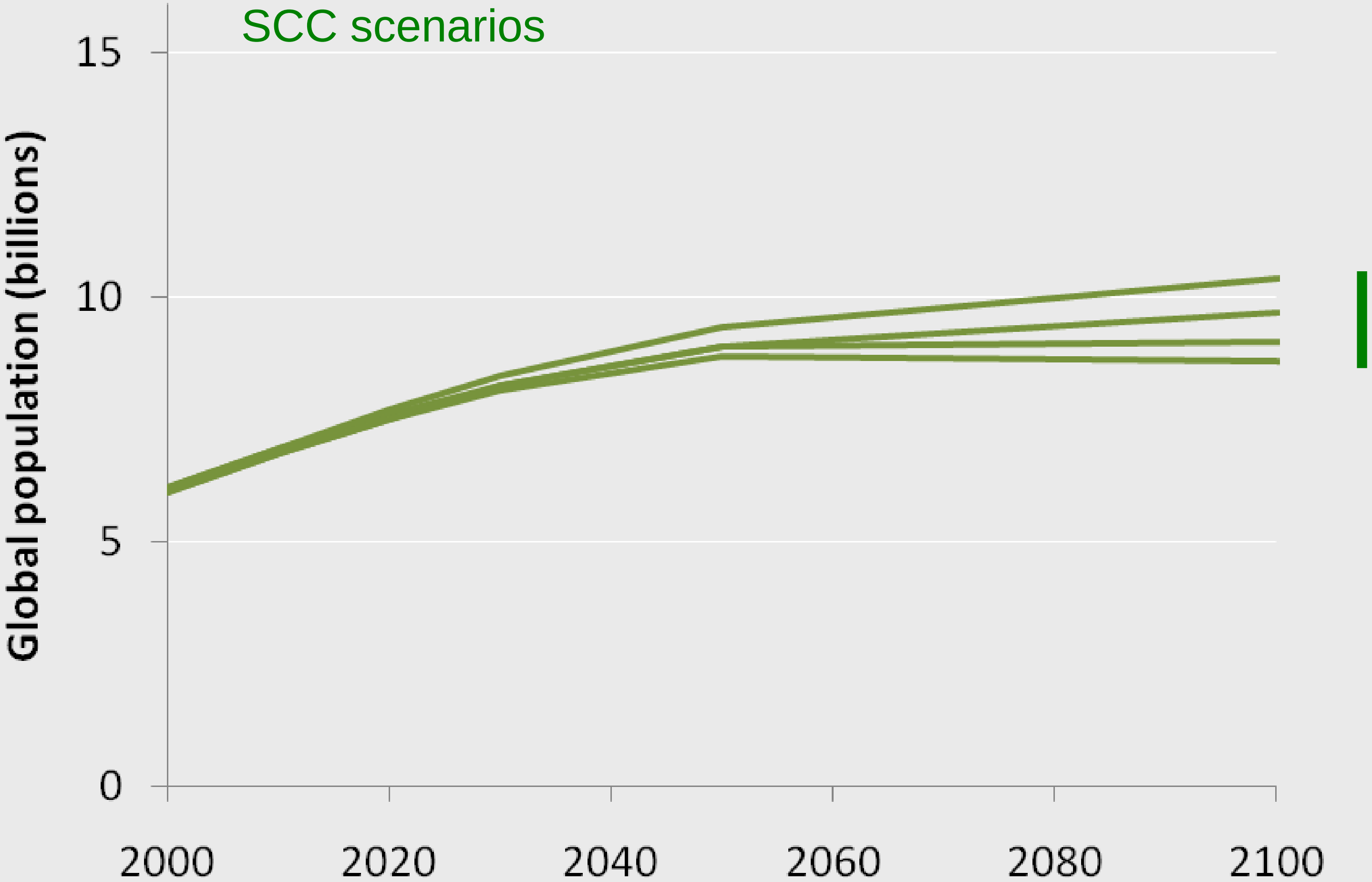
- **Population, GDP, CO2 emissions, non-CO2 forcing**
- **SCC approach**
  - "we aimed to select scenarios that span most of the plausible ranges of outcomes for these variables"
  - Select 5 scenarios from EMF-22 exercise, based on 4 models
  - "EMF BAU scenarios represent the modelers' judgment of the ***most likely pathway*** absent mitigation policies to reduce greenhouse gas emissions, rather than the wider range of possible outcomes. Nevertheless, ***these views of the most likely outcome span a wide range***…"
  - Extend from 2100 to 2300 for SCC calculation

Population and Uncertainty

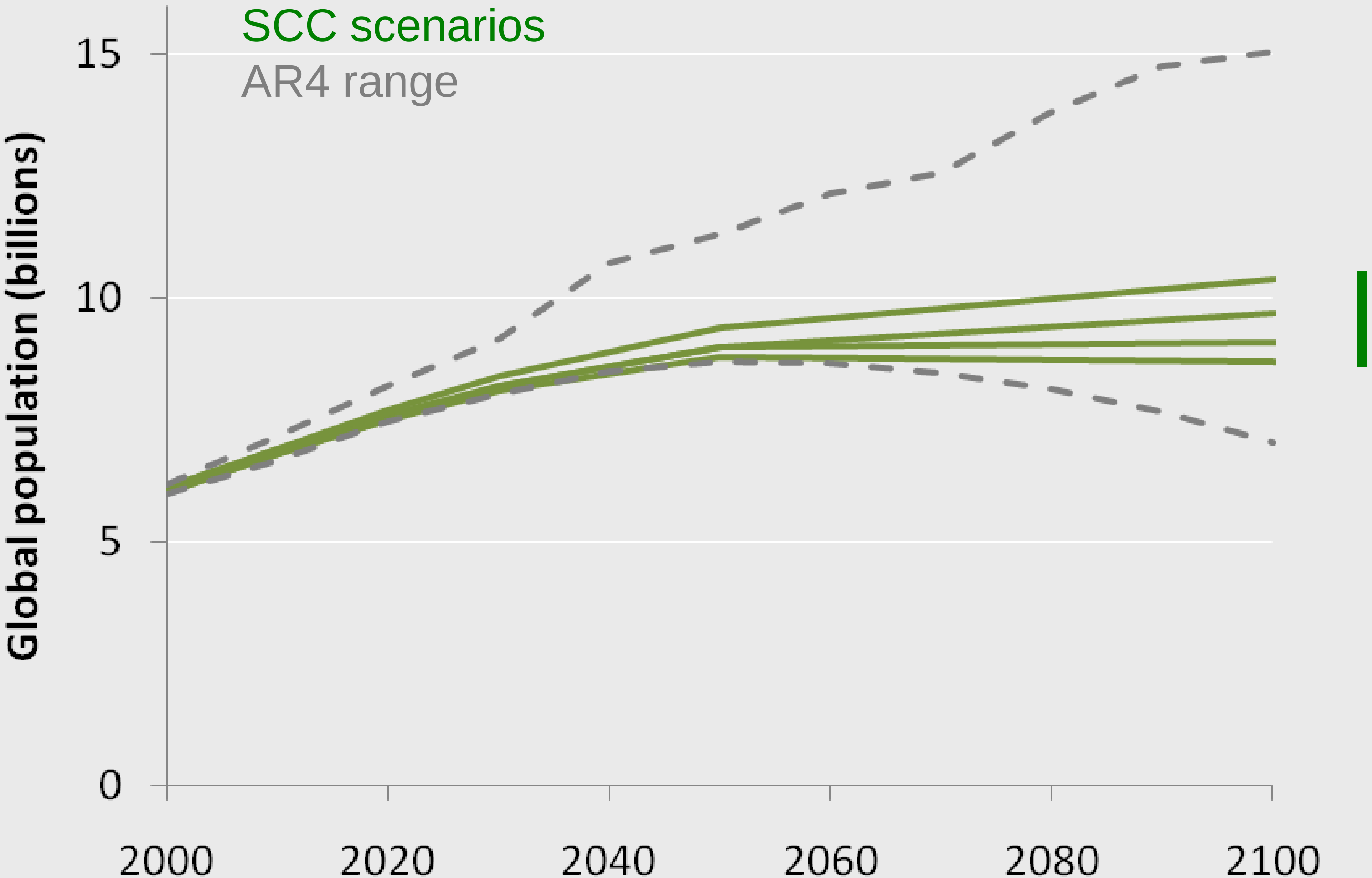
- **2010-2040**
  - **meaningful projections with well characterized uncertainty**
- **2040-2080**
  - **uncertainty begins to compound, but can still be usefully characterized**
- **Beyond 2080**
  - **compounding uncertainty, speculation about new conditions, limits, and feedbacks**

See UN, 2004; Lutz & Scherbov, 2008.

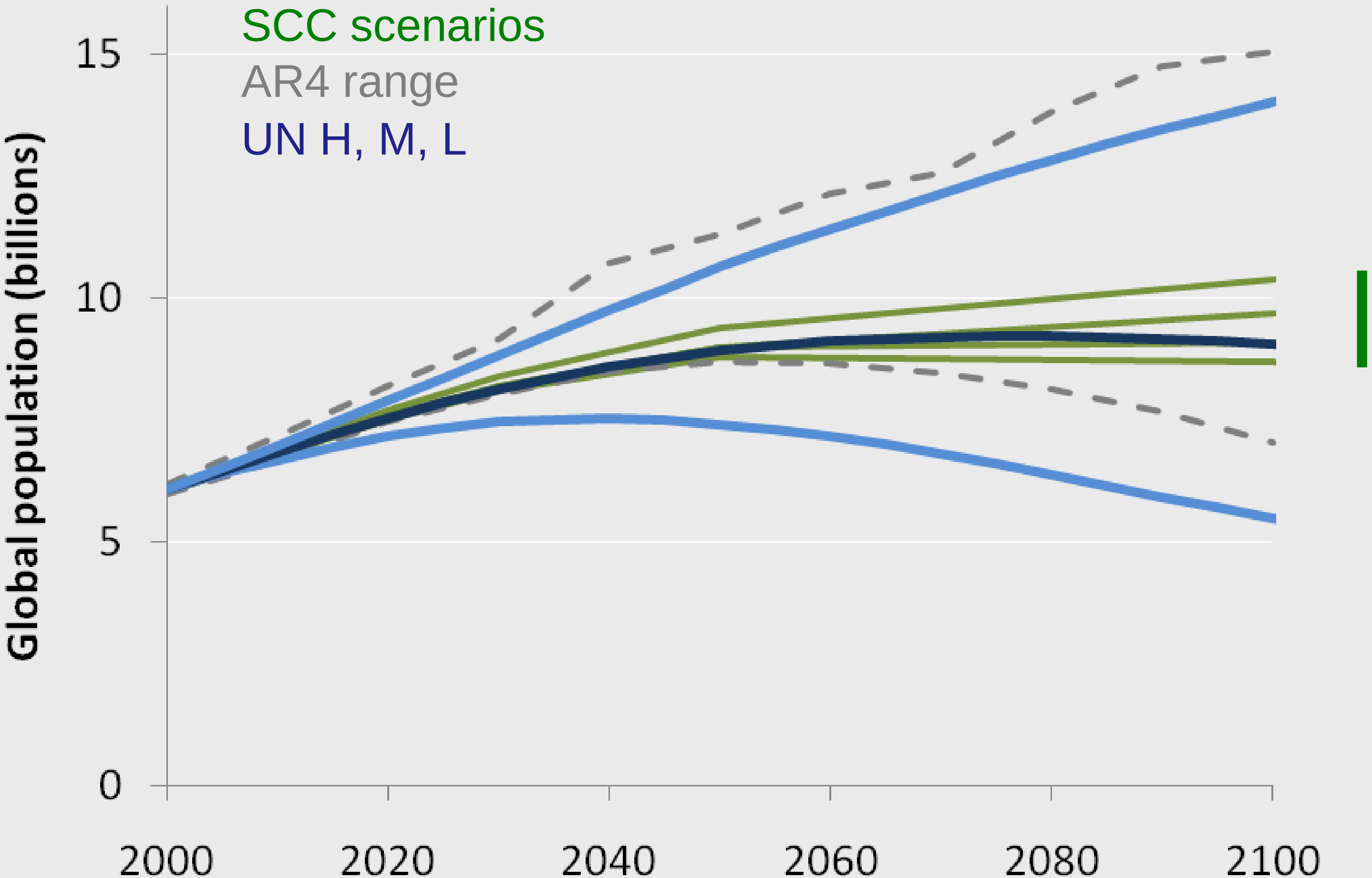
Global Population to 2100



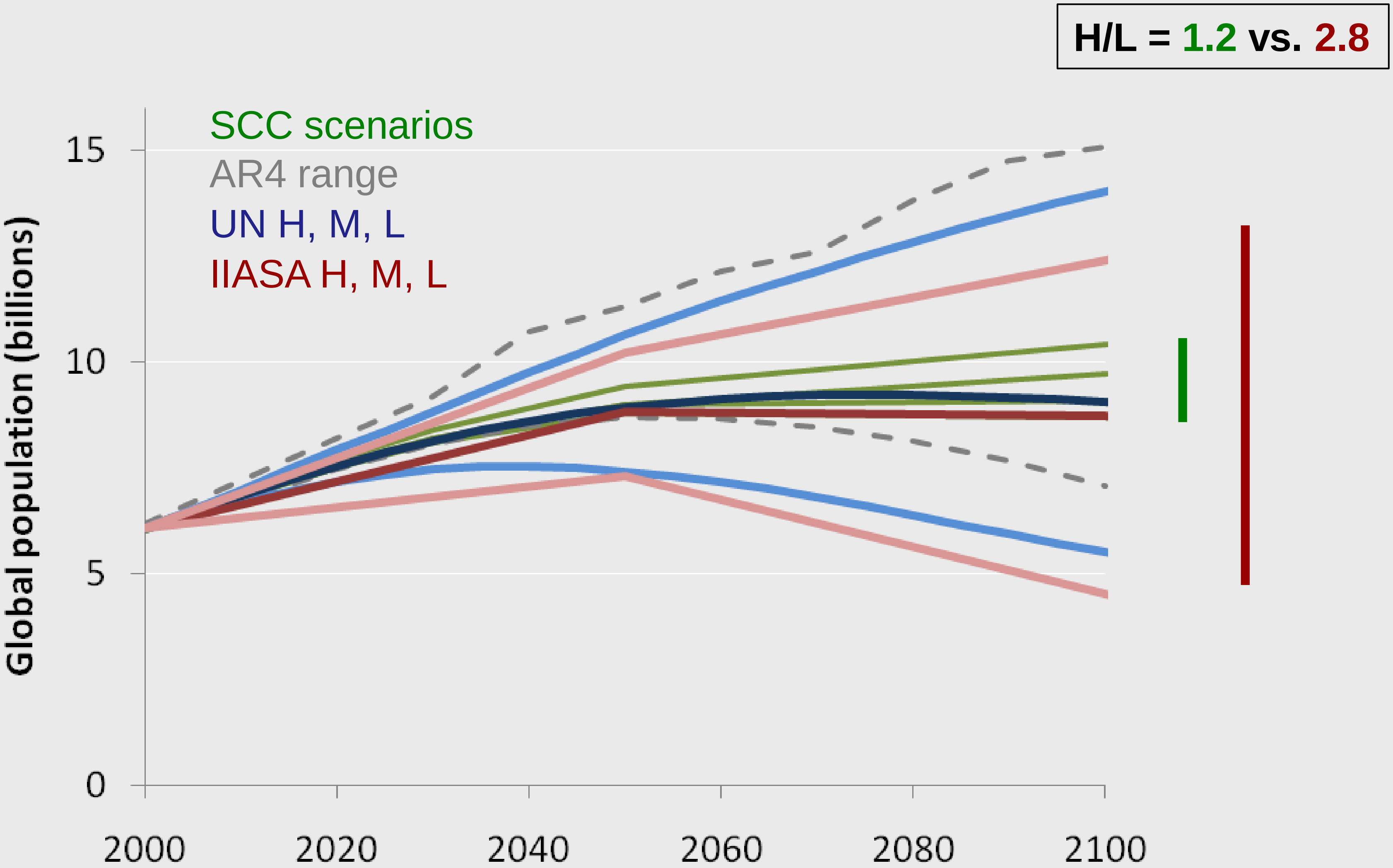
Global Population to 2100



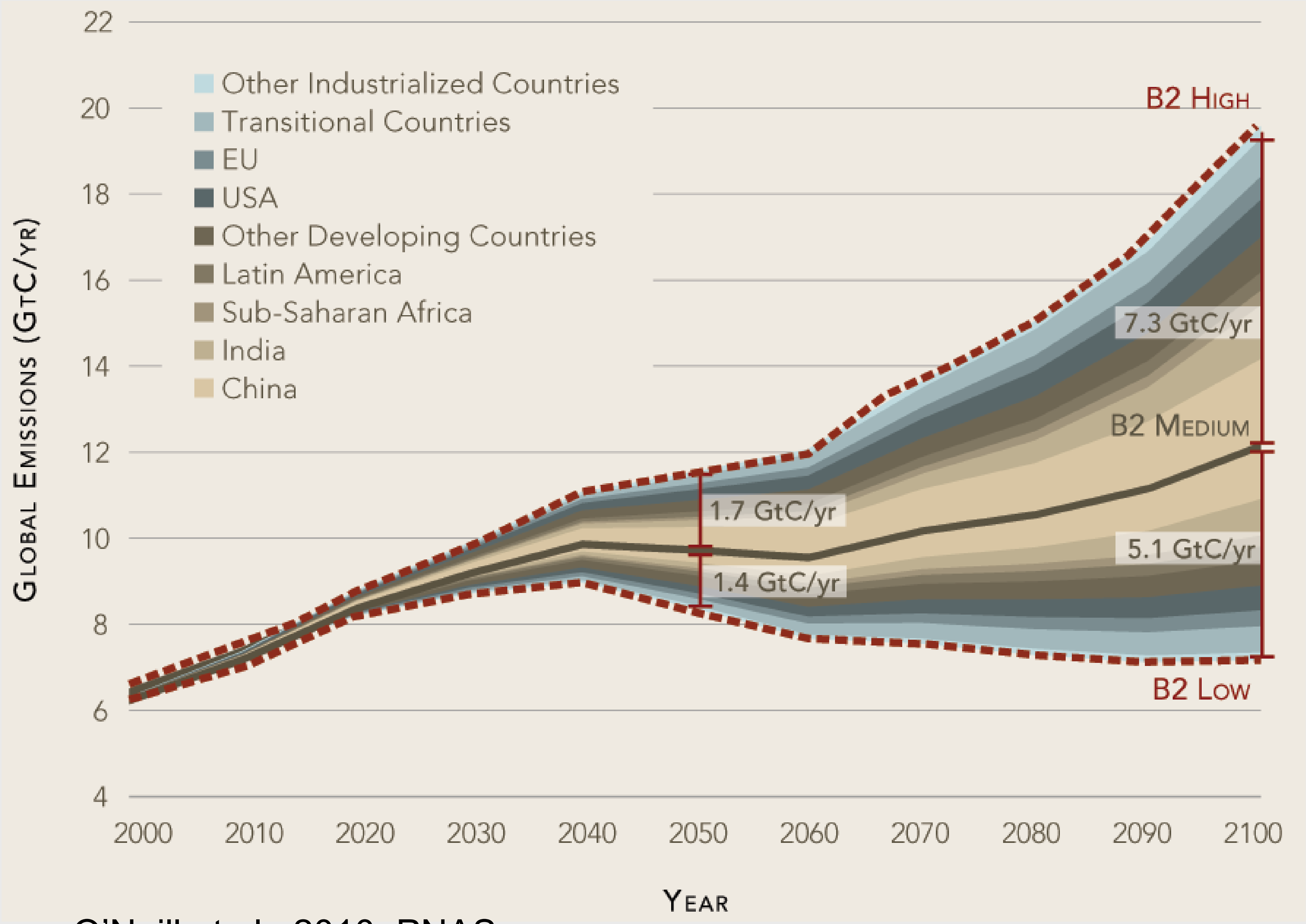
Global Population to 2100



Global Population to 2100



Effect of population on CO2 emissions

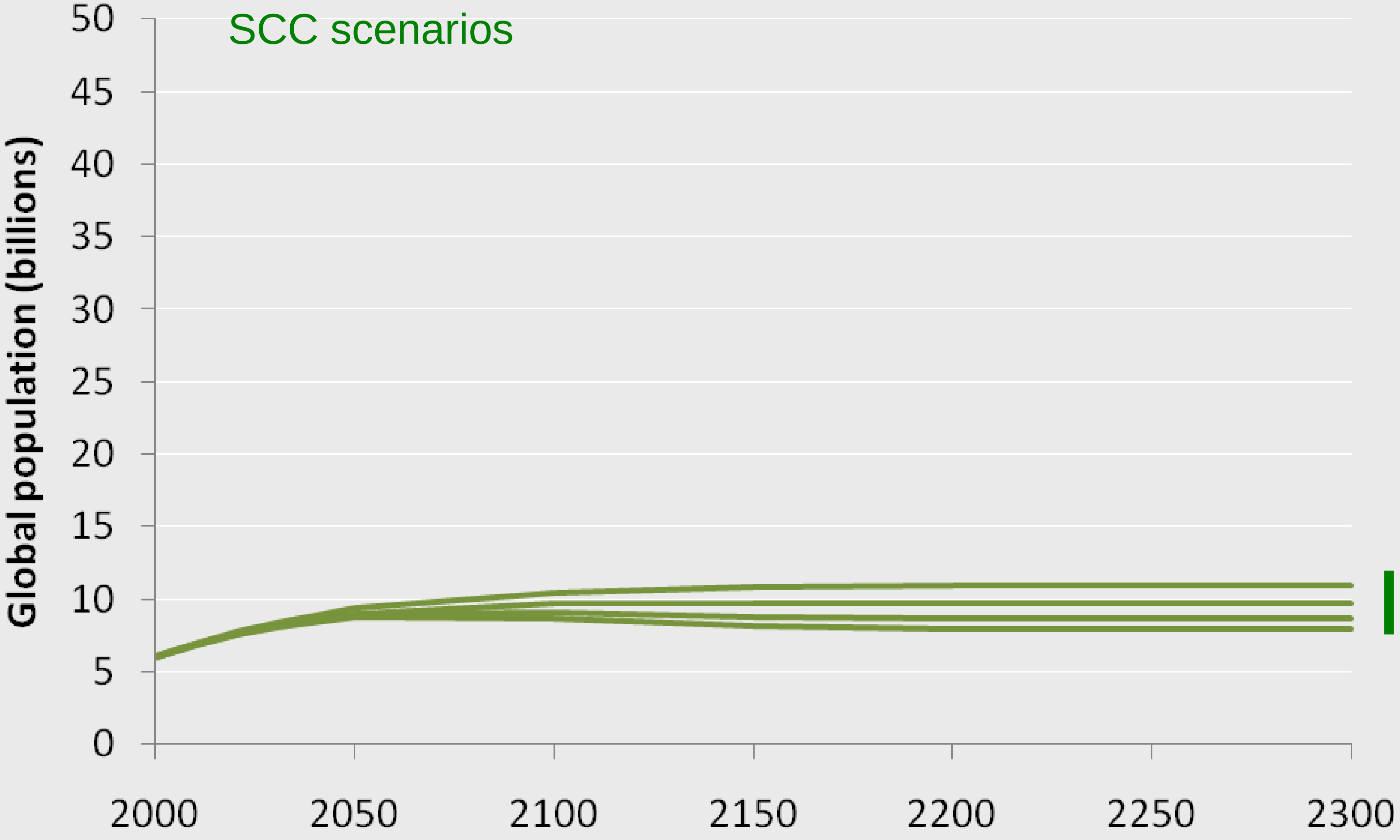


Source: O'Neill et al., 2010, PNAS.

SCC extrapolation to 2300

- Growth rates at end of 21st century decline linearly to zero by 2200
- "reasonably consistent with the United Nations long run population forecast, which estimates global population to be fairly stable after 2150 in the medium scenario"

Global Population to 2300

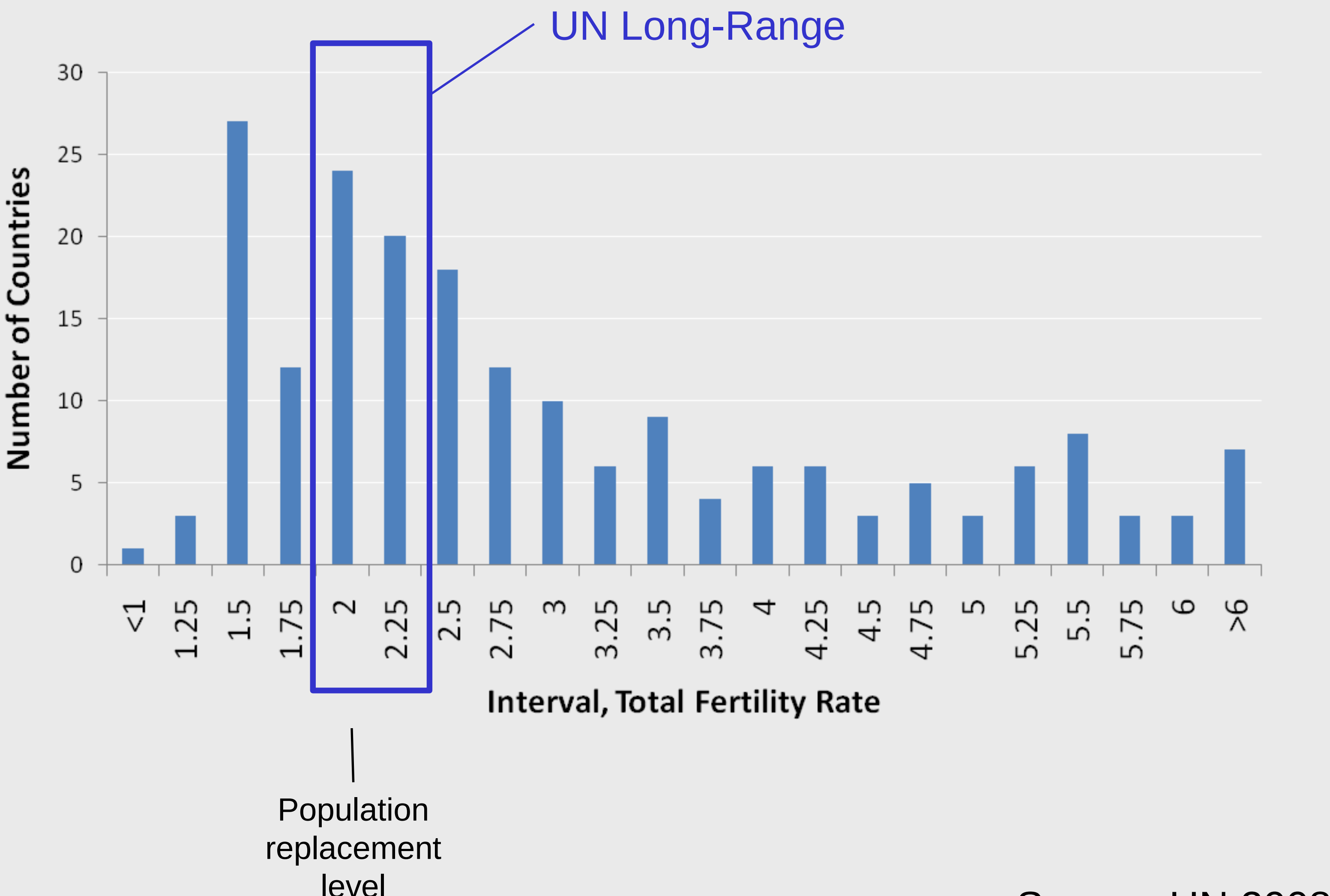


UN Long-Range Projections

- 2000-2300
- Country-specific
- Three fertility variants
  - Long-run convergence at 1.85, 2.05, 2.35
- Life expectancy increases throughout the period
  - from ~75 in 2050 to ~95 in 2300
- Migration zero after 2050

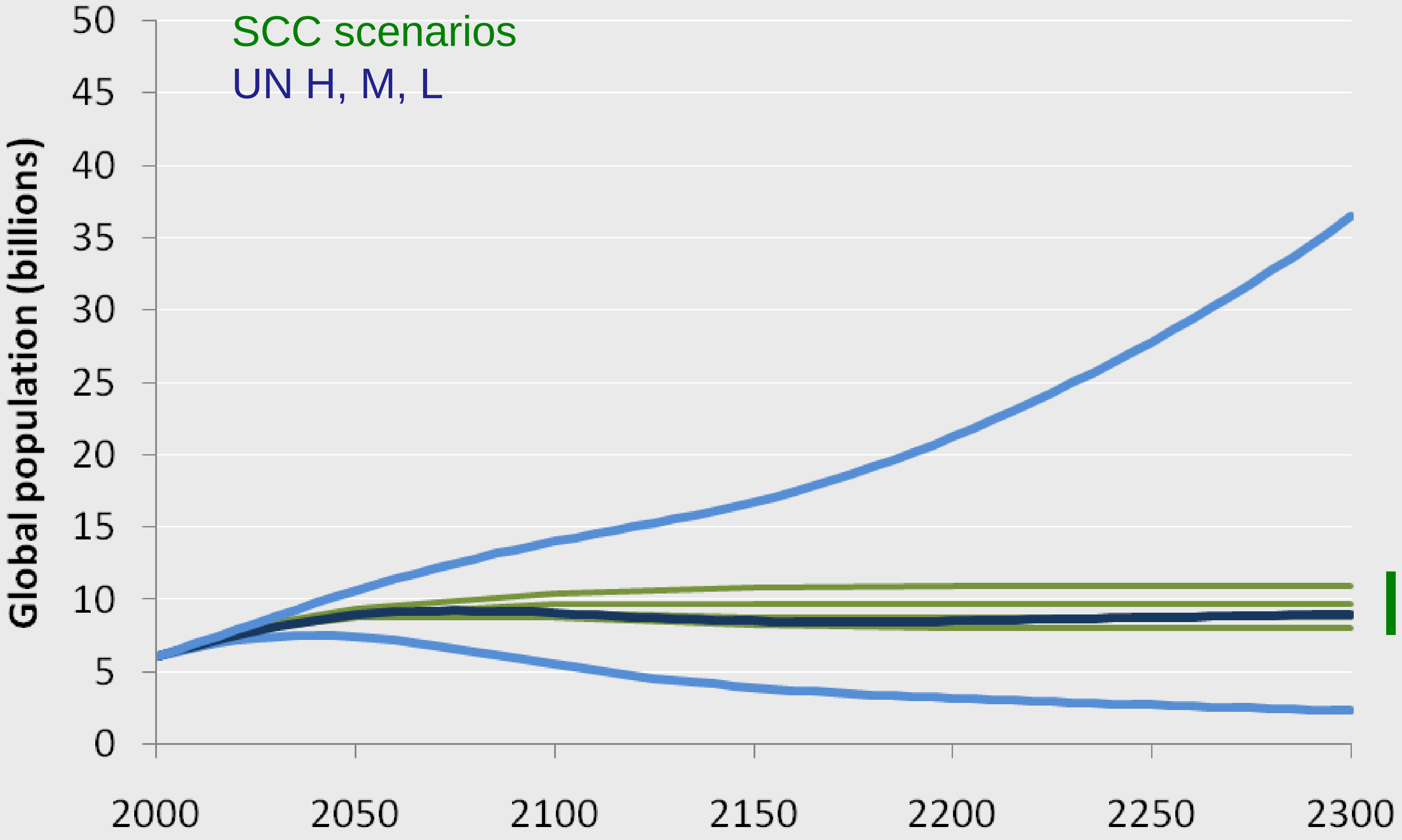
- Medium to 2300 is not the most likely! Designed to produce a roughly stable population size
- Value: illustrate the implications of small differences in future fertility levels

Distribution of national fertility rates, 2005-2010



Source: UN 2008.

Global Population to 2300

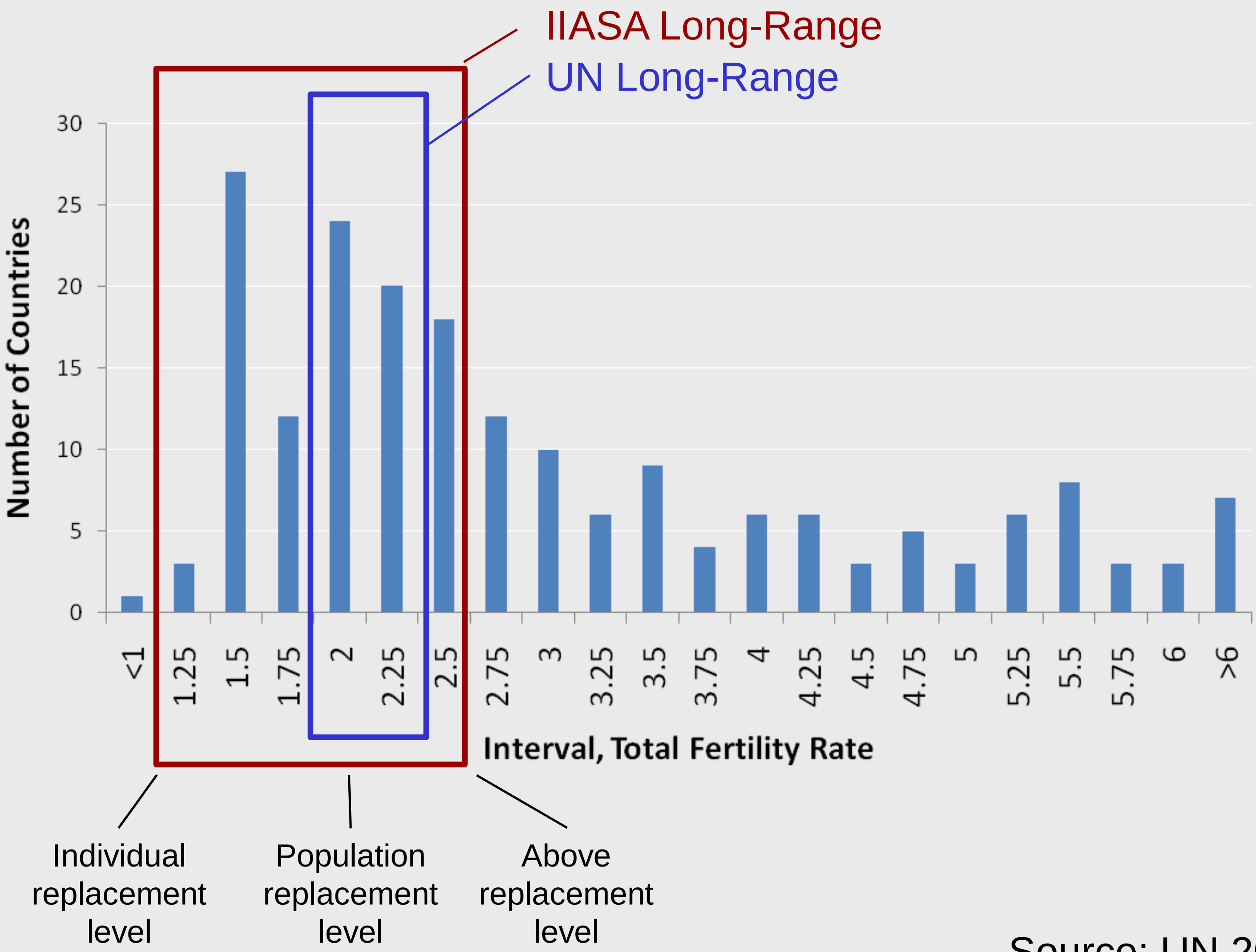


IIASA Long-Range Projections

- 2000-2300
- 13 world regions
- Four long-term fertility levels
  - Long-run convergence at 1.0, 1.5, 2.0, 2.5
- Life expectancy increases throughout the period
  - maximum life expectancy of 120
- Migration zero after 2080

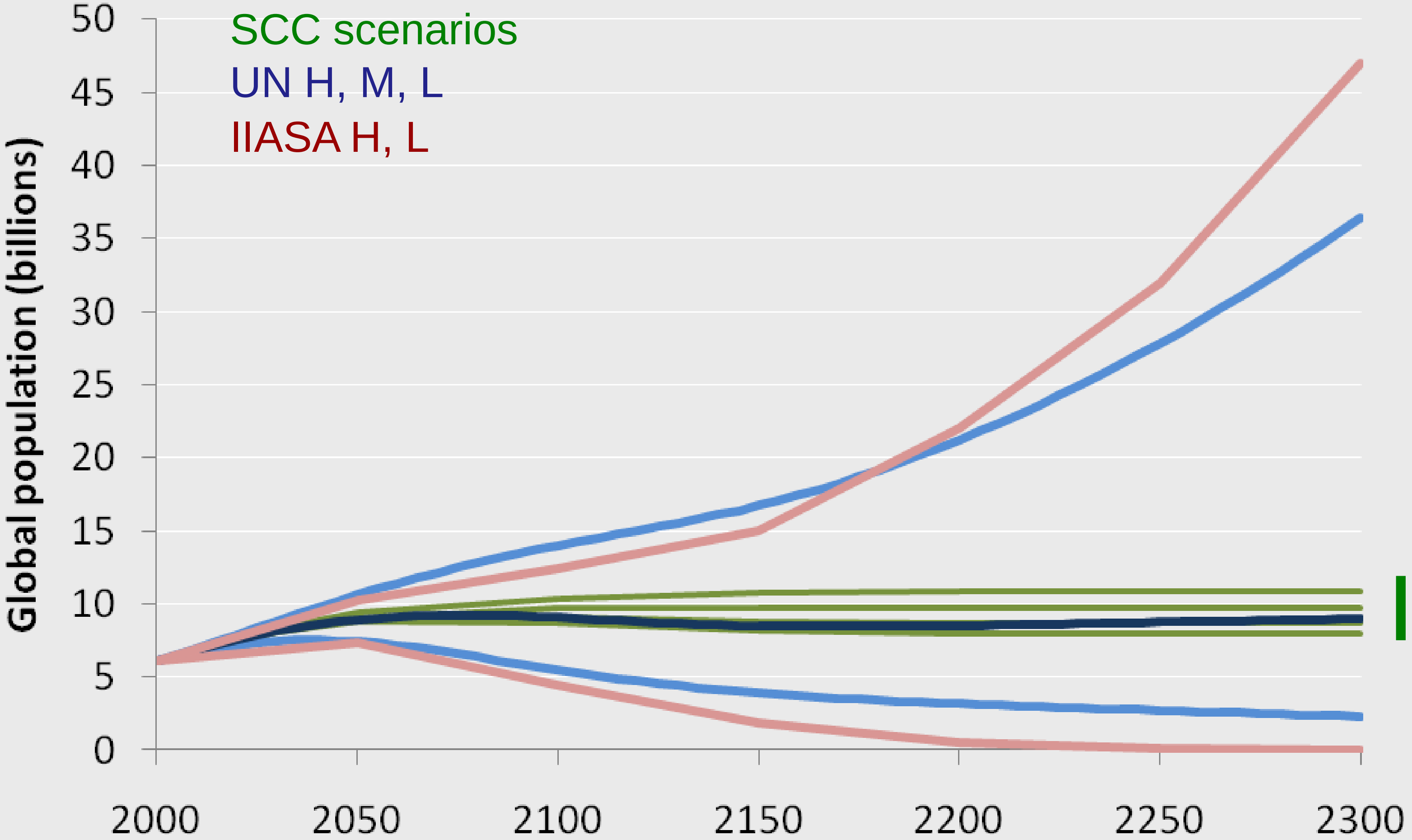
- Extensions to 2300 are not probabilistic
- Value: illustrate the implications of plausible range of future fertility levels

Distribution of national fertility rates, 2005-2010

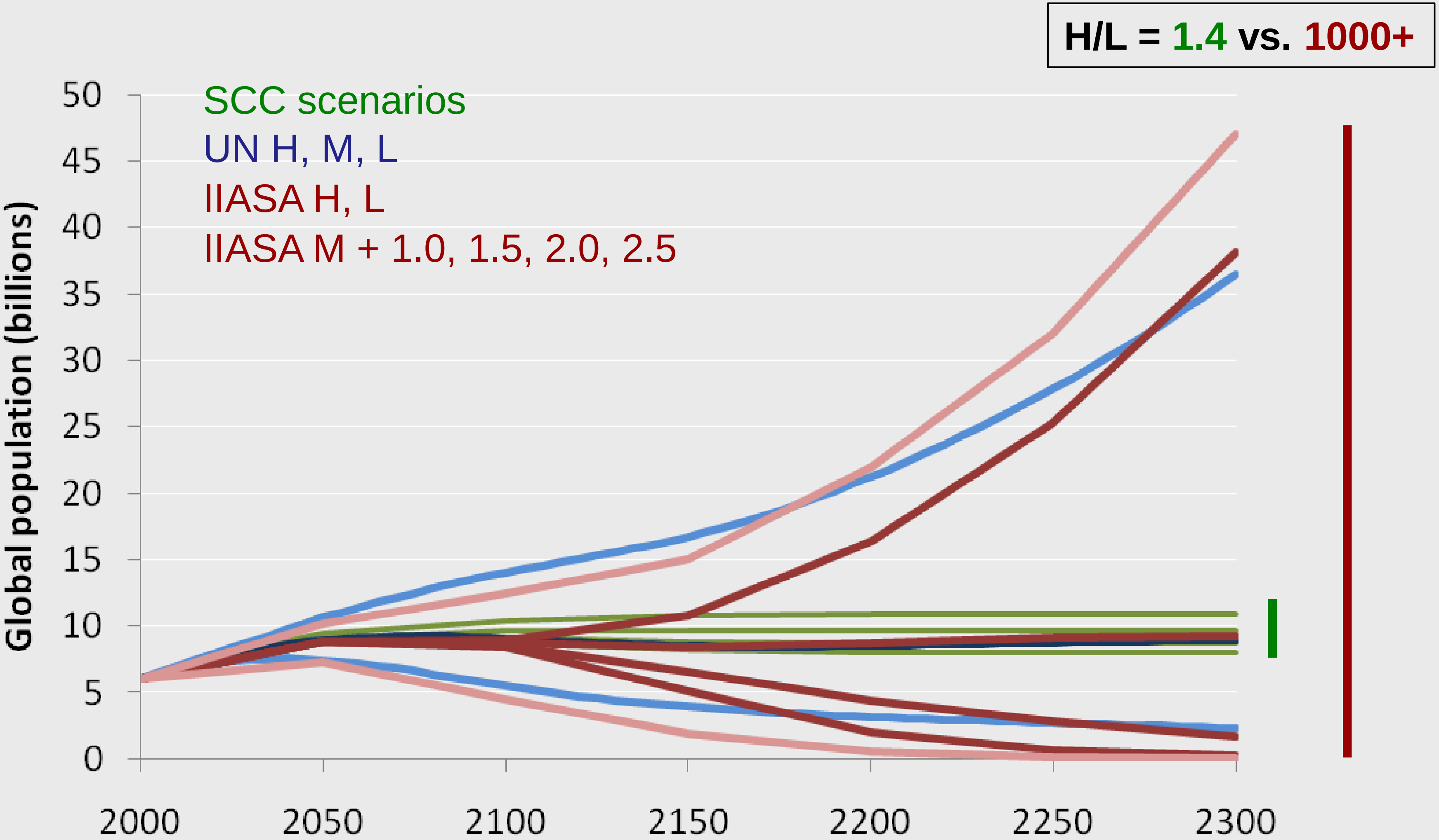


Source: UN 2008.

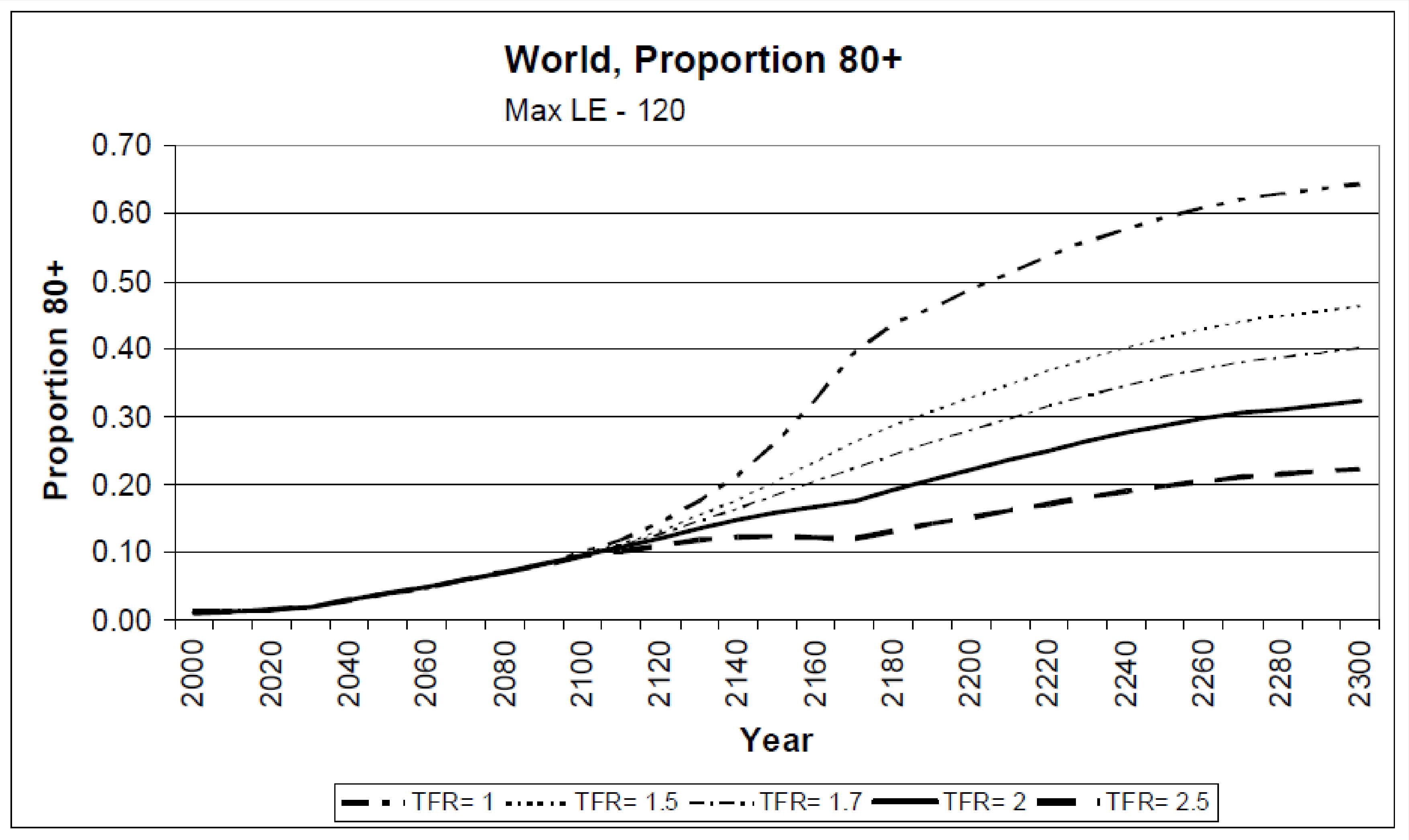
Global Population to 2300



Global Population to 2300

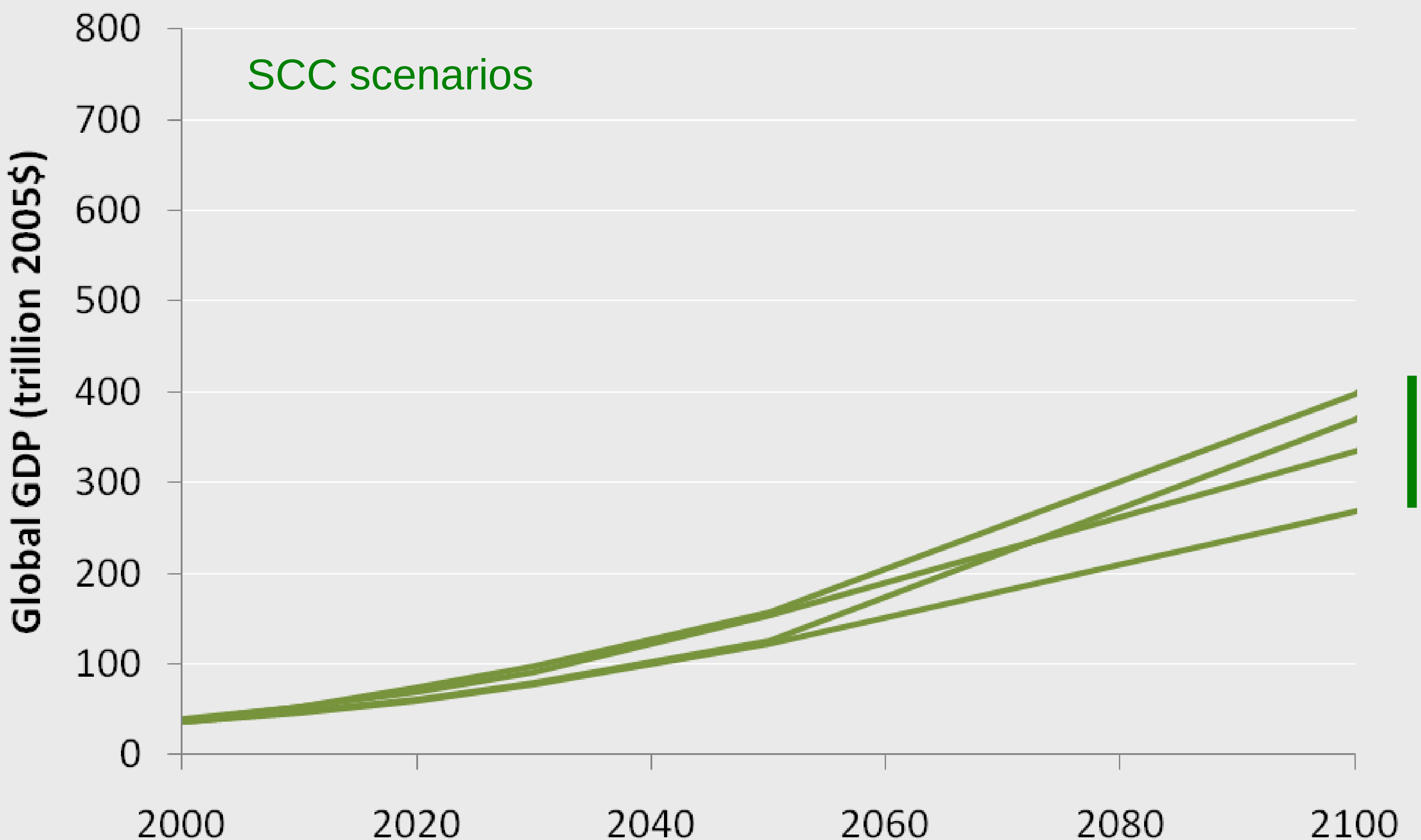


Global Population Age Structure



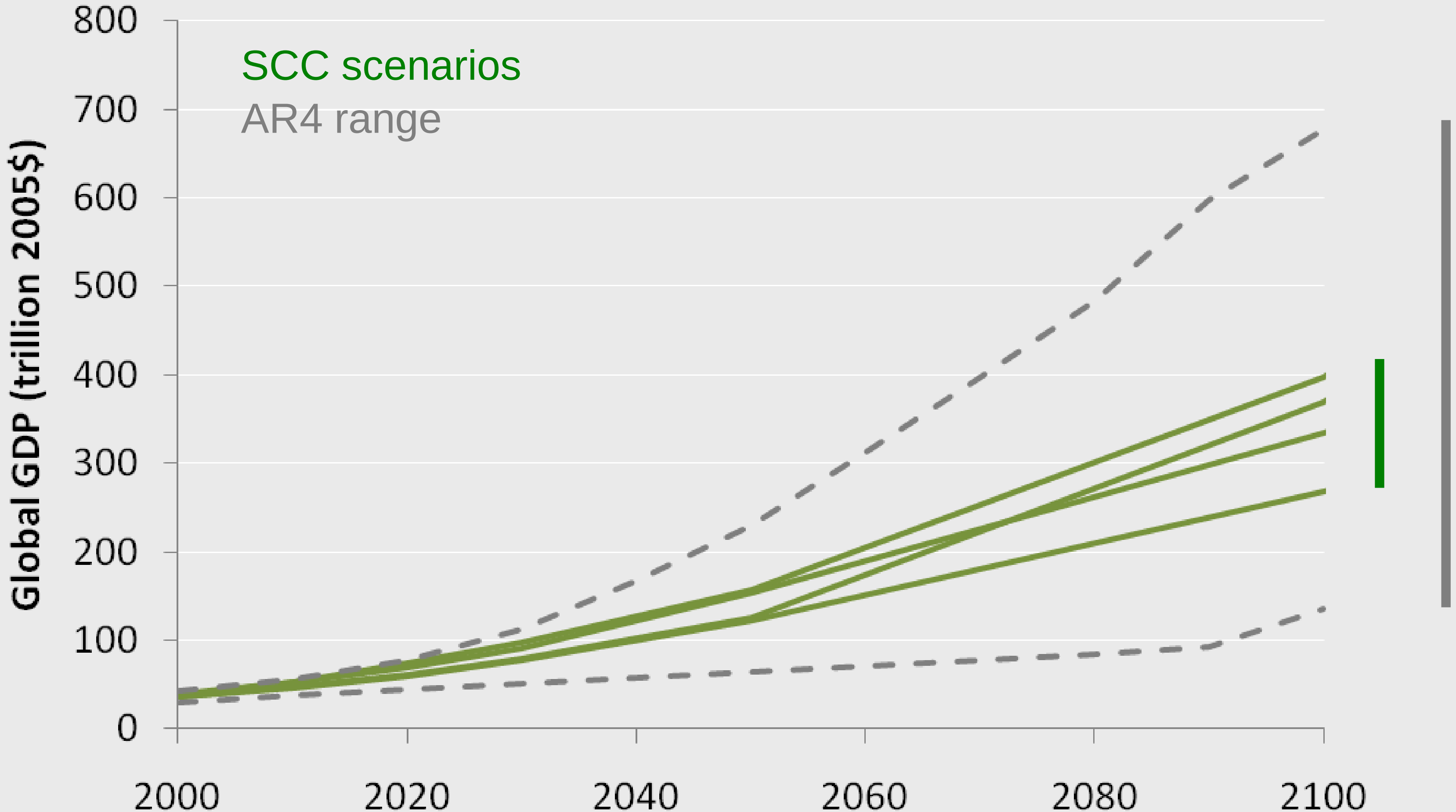
Source: Lutz & Scherbov, 2008.

Global GDP to 2100



Global GDP to 2100

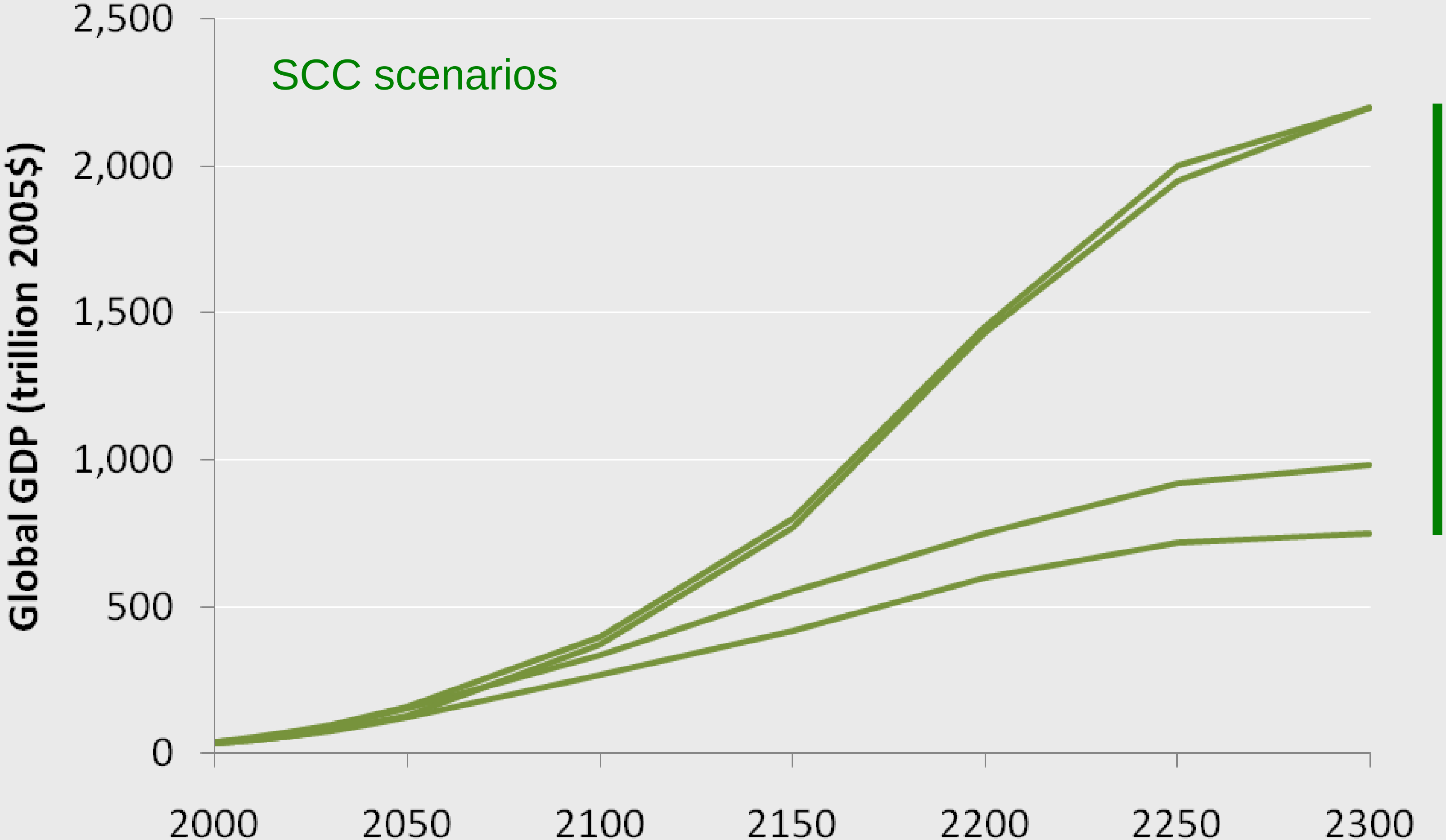
H/L = 1.5 vs. 5.0



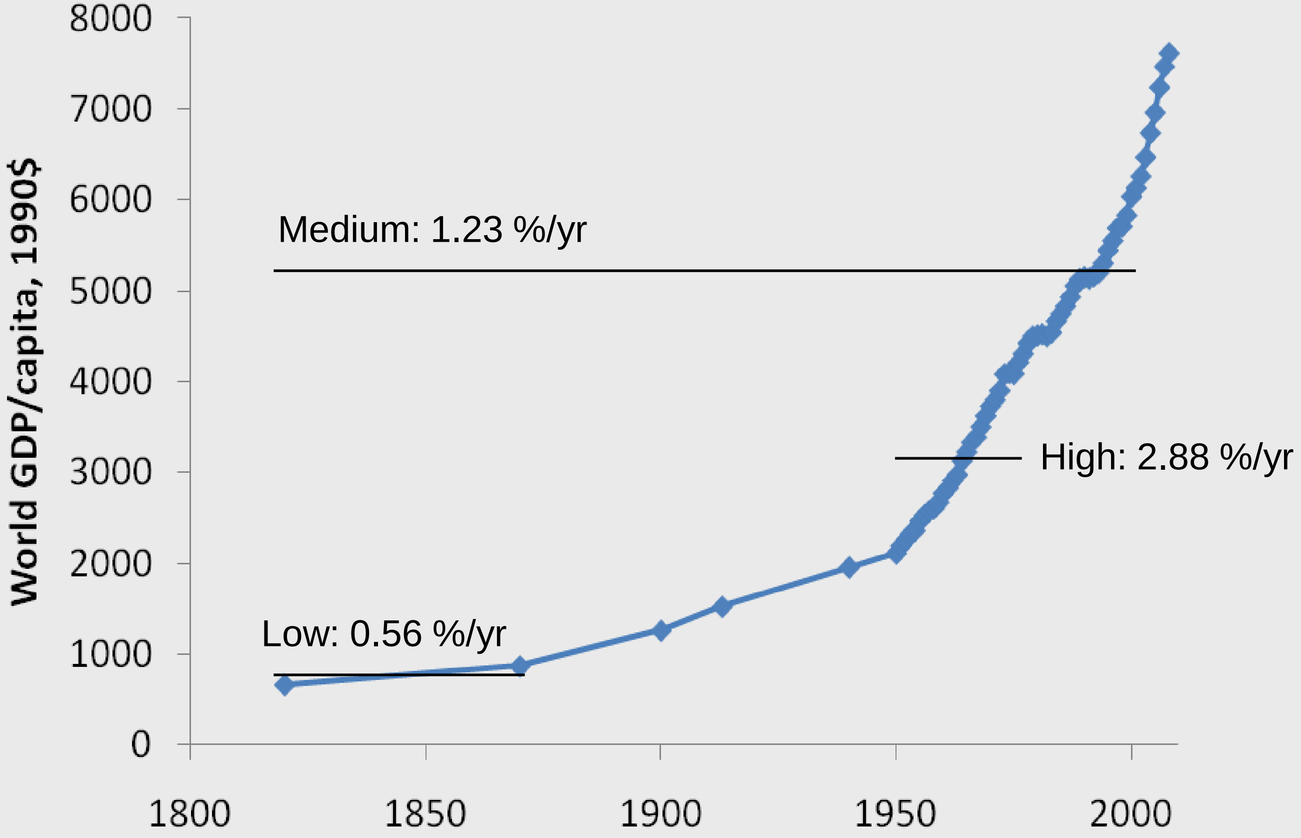
SCC extrapolation to 2300

- Growth rates of per capita GDP at end of 21st century decline linearly to zero by 2300
- Based on idea that "increasing scarcity of natural resources and the degradation of environmental sinks available for assimilating pollution from economic production activities may eventually overtake the rate of technological progress"

Global GDP to 2300

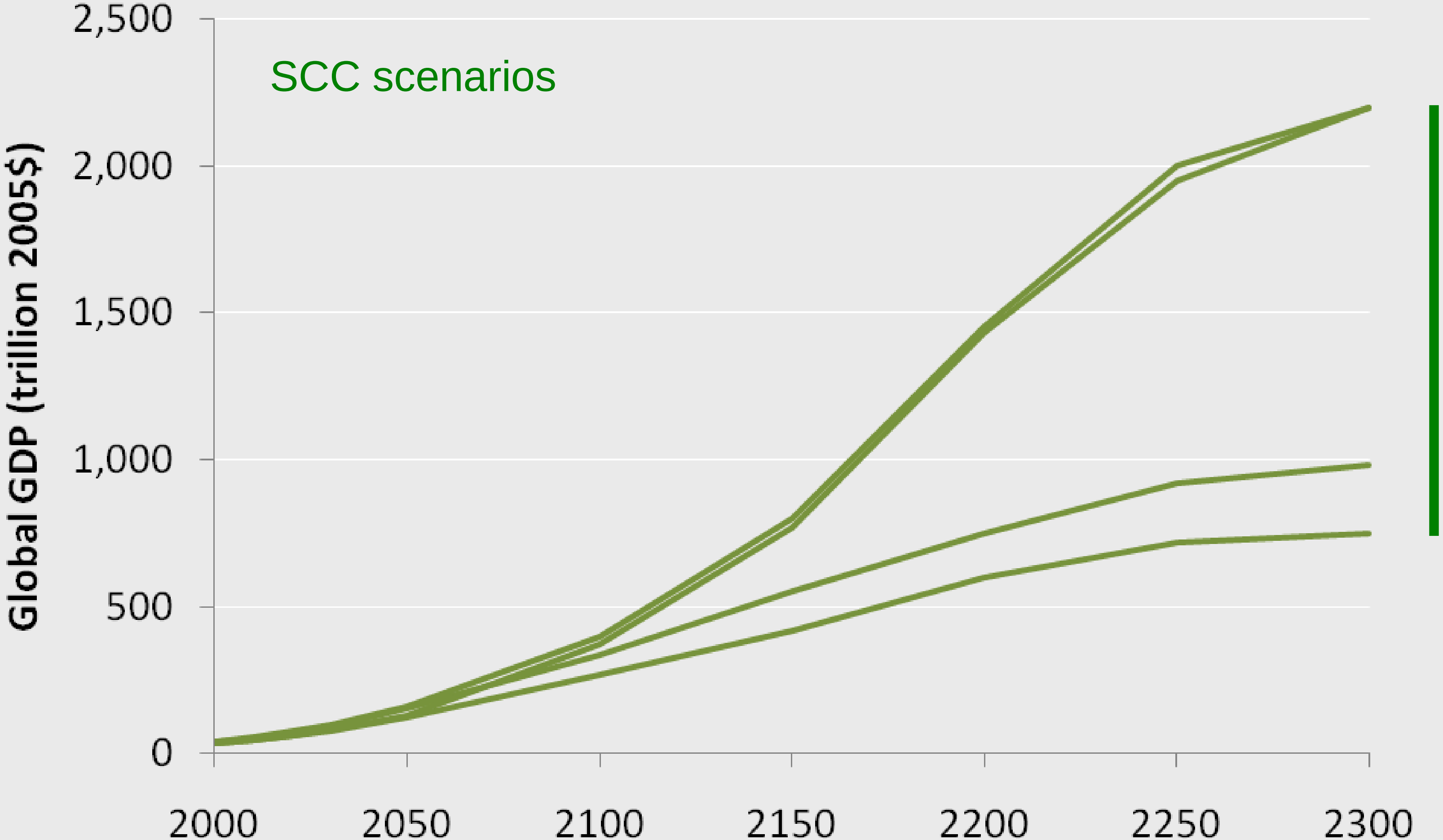


GDP Projections Based on Historical Experience

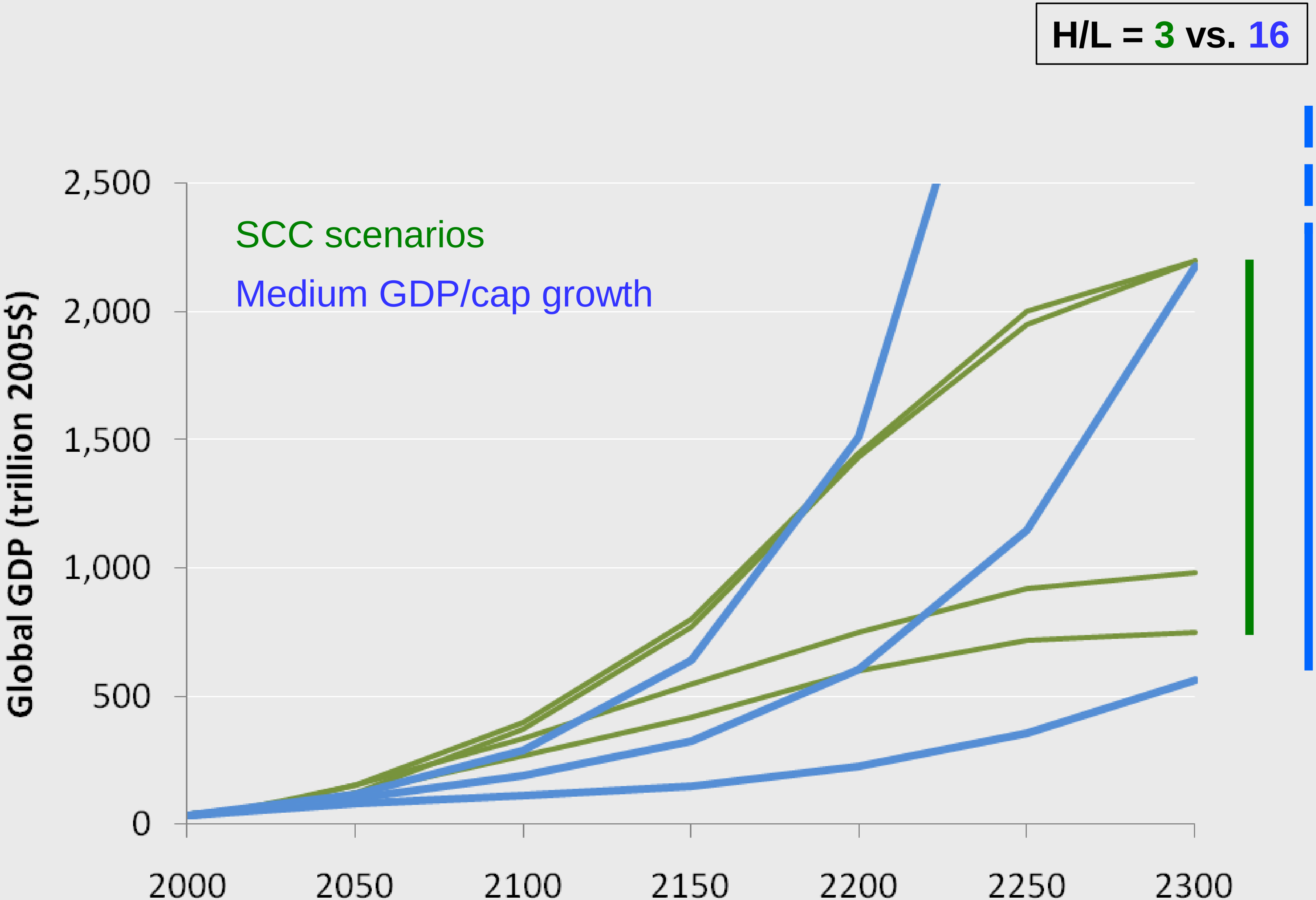


Source: Date from Maddison, 2010. After Tonneson, 2008.

Global GDP to 2300

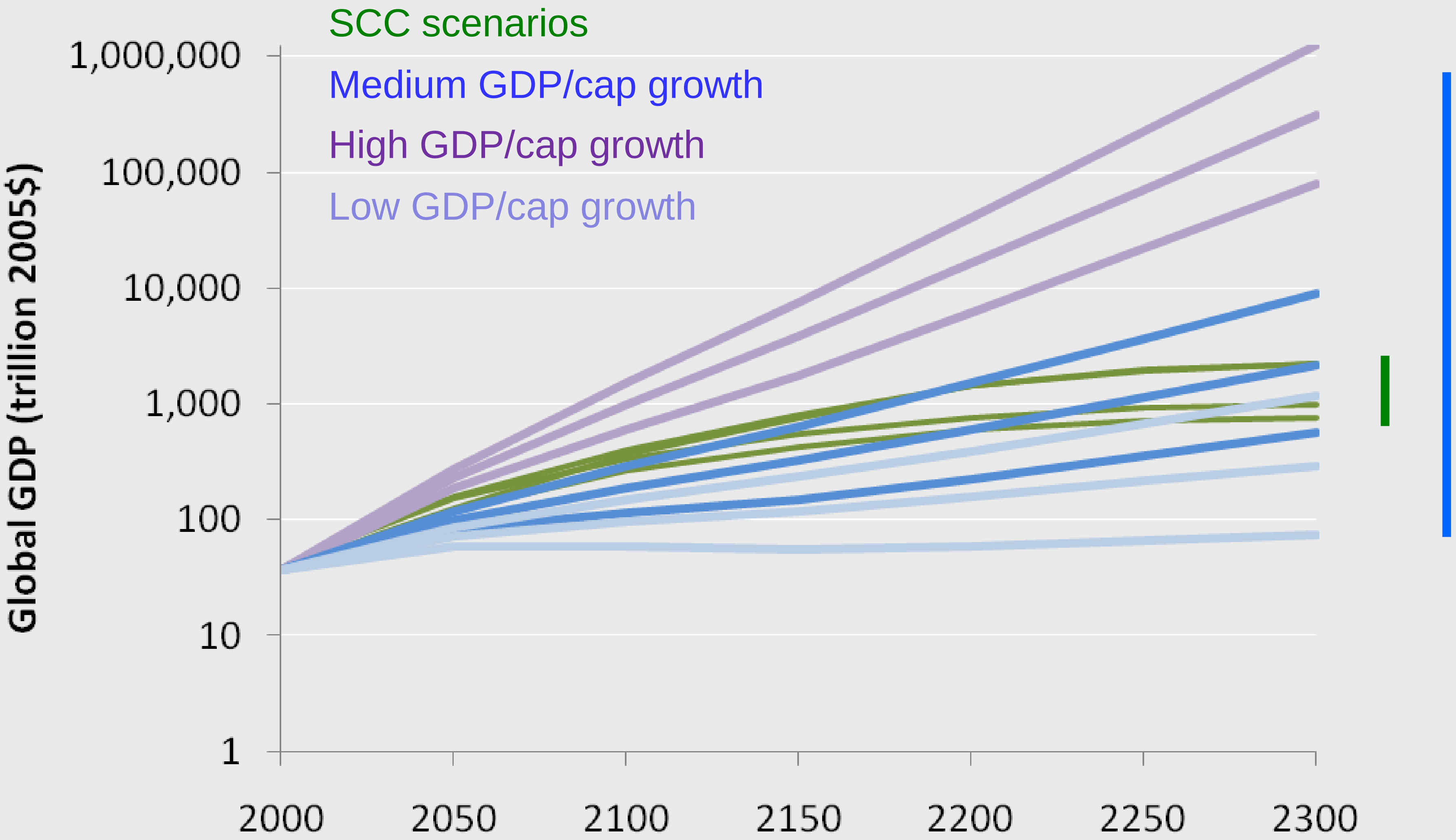


Global GDP to 2300

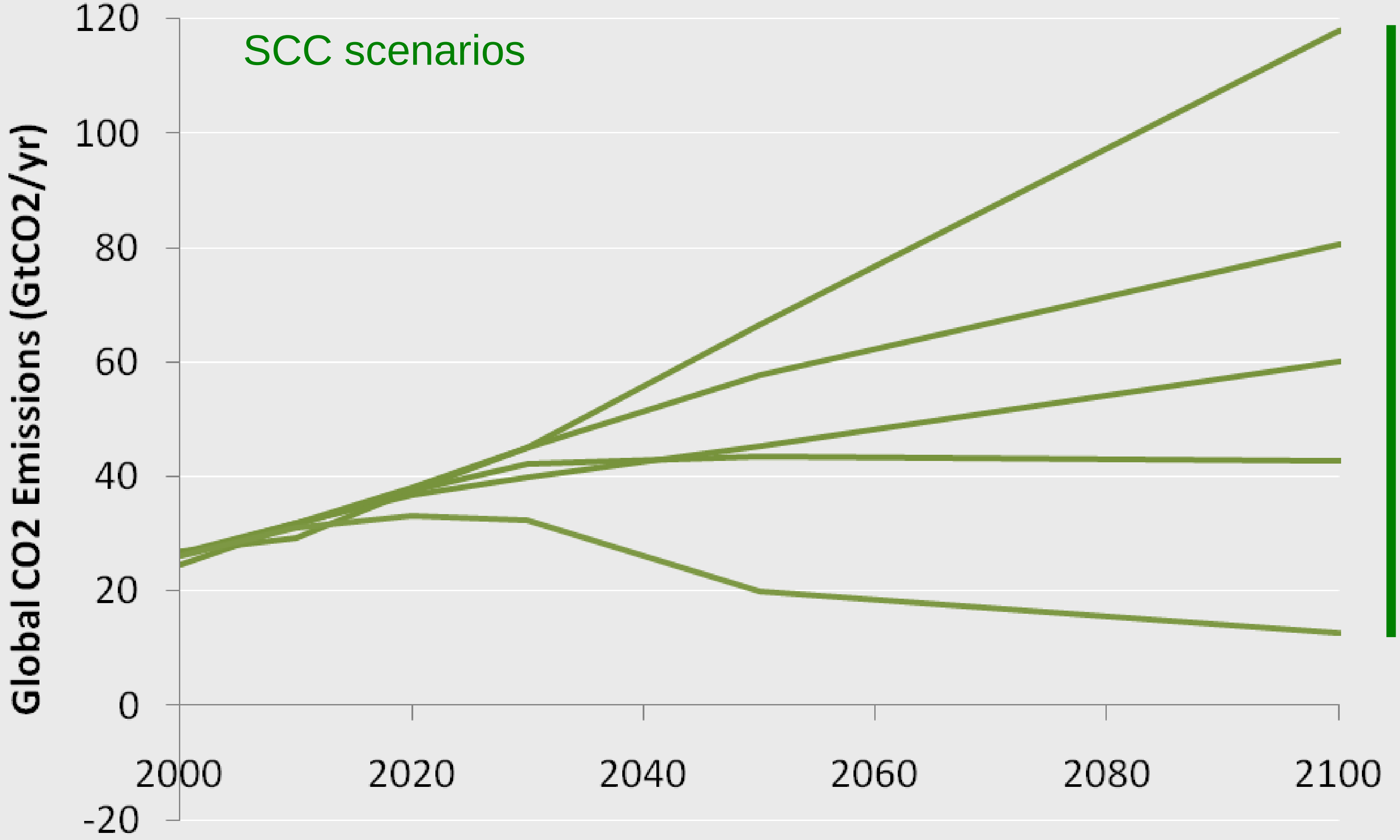


Global GDP to 2300

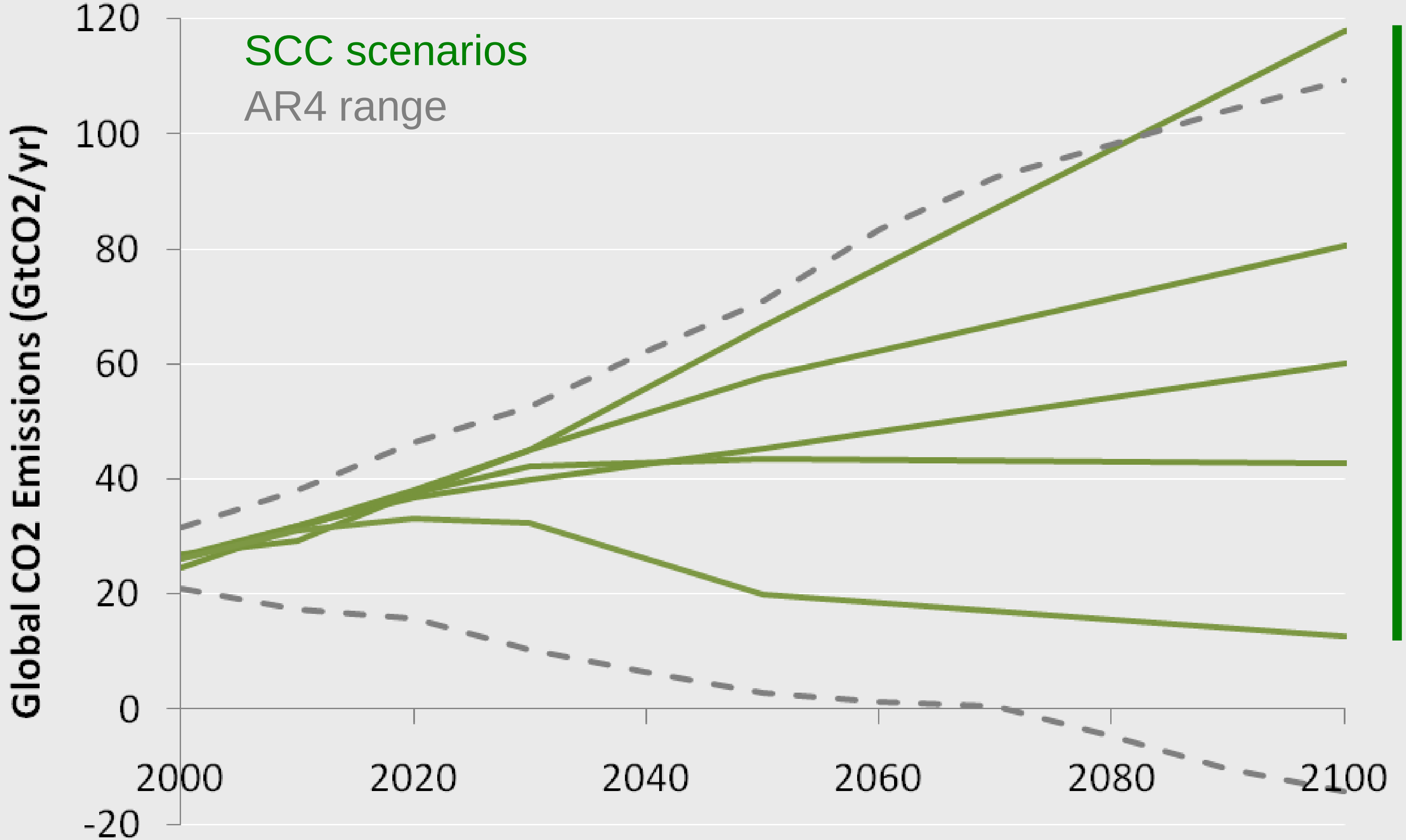
H/L = 3 vs. 10^4



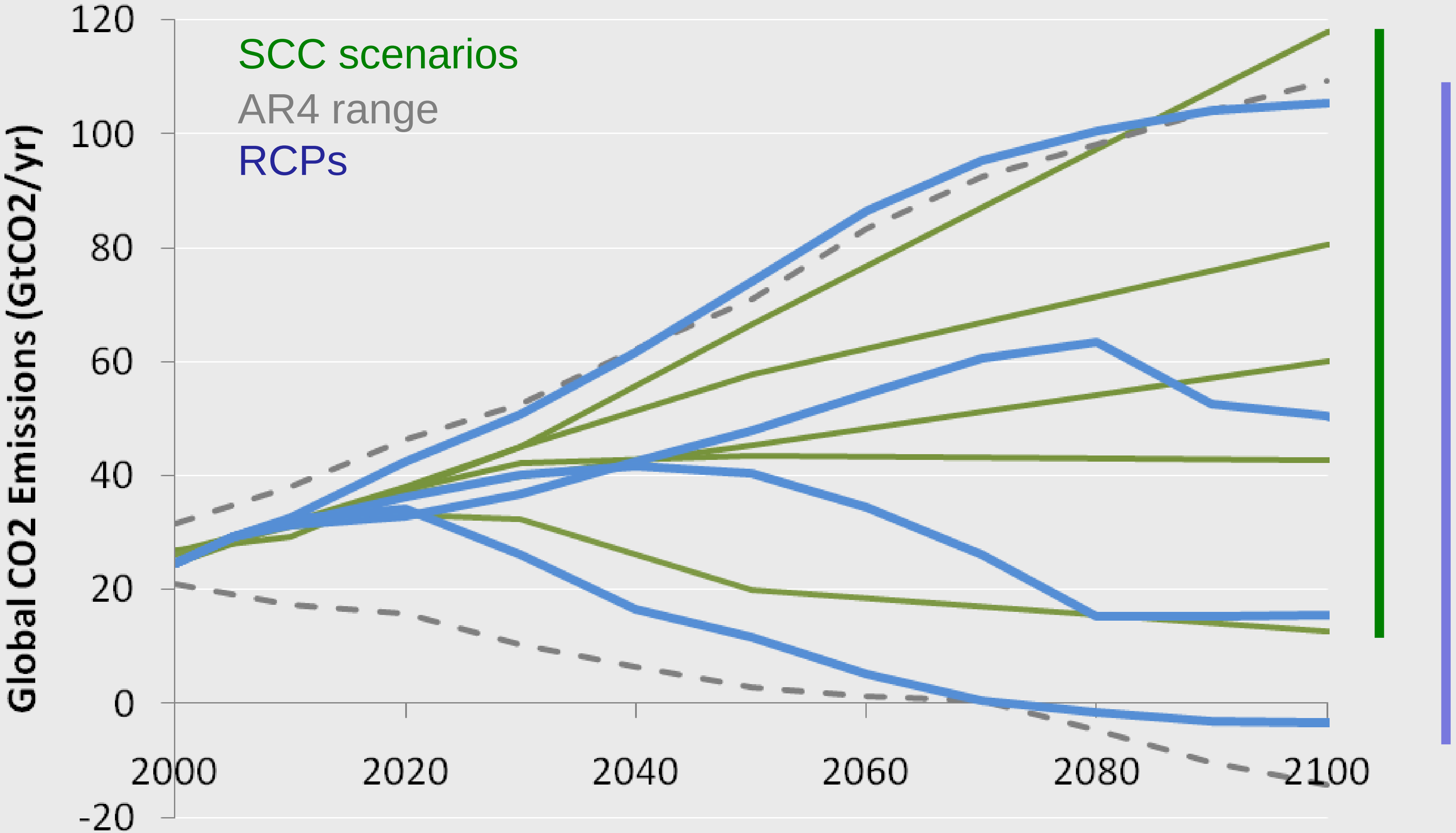
Global CO2 Emissions to 2100



Global CO2 Emissions to 2100



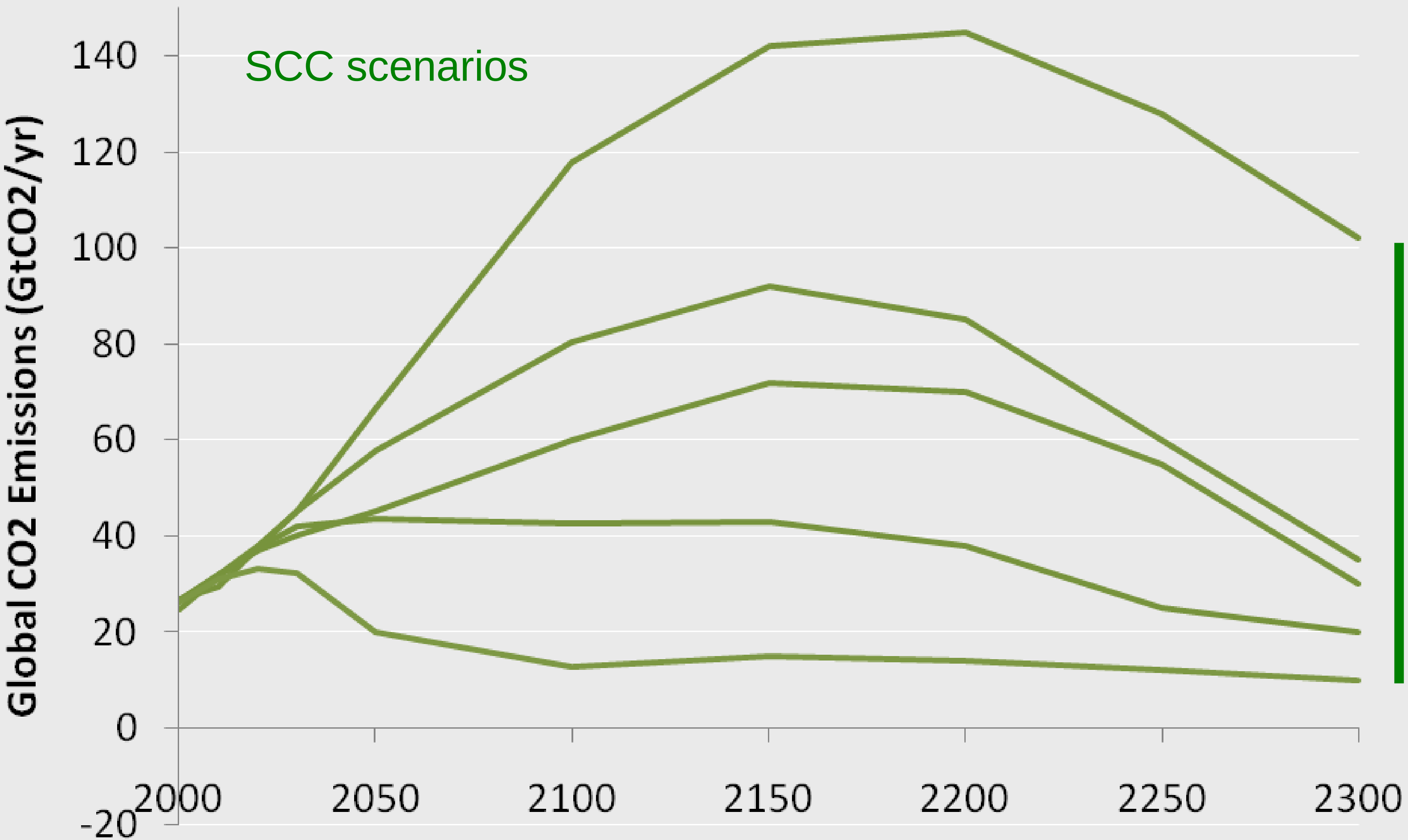
Global CO2 Emissions to 2100



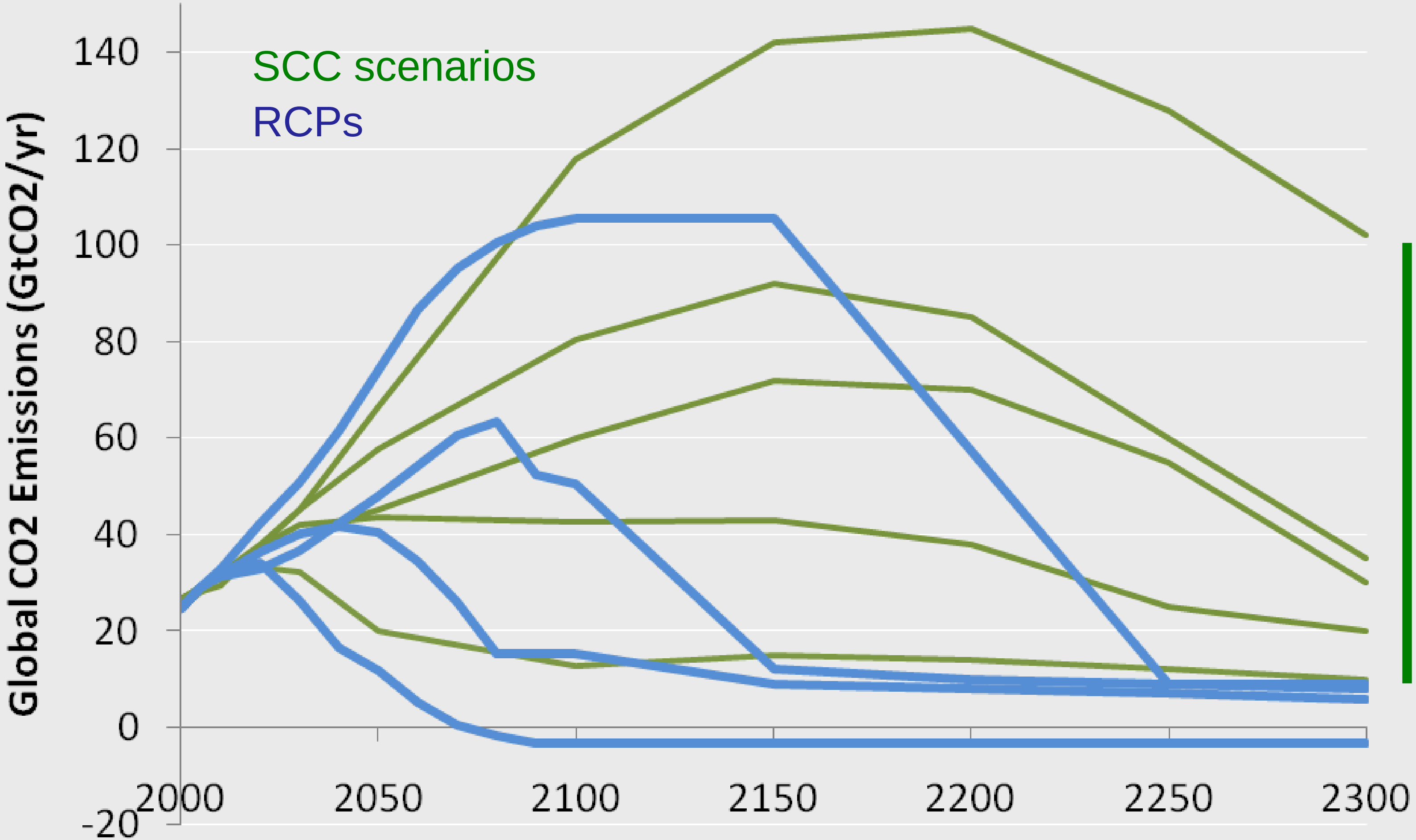
SCC extrapolation to 2300

- Growth rates (decline rates) of carbon intensity (CO_2/GDP) from end of 21st century maintained through 2300
- "assumes that technological improvements and innovations in the areas of energy efficiency and other carbon reducing technologies … will continue to proceed at roughly the same pace that is projected to occur towards the end of the forecast period"

Global Fossil CO2 Emissions to 2300

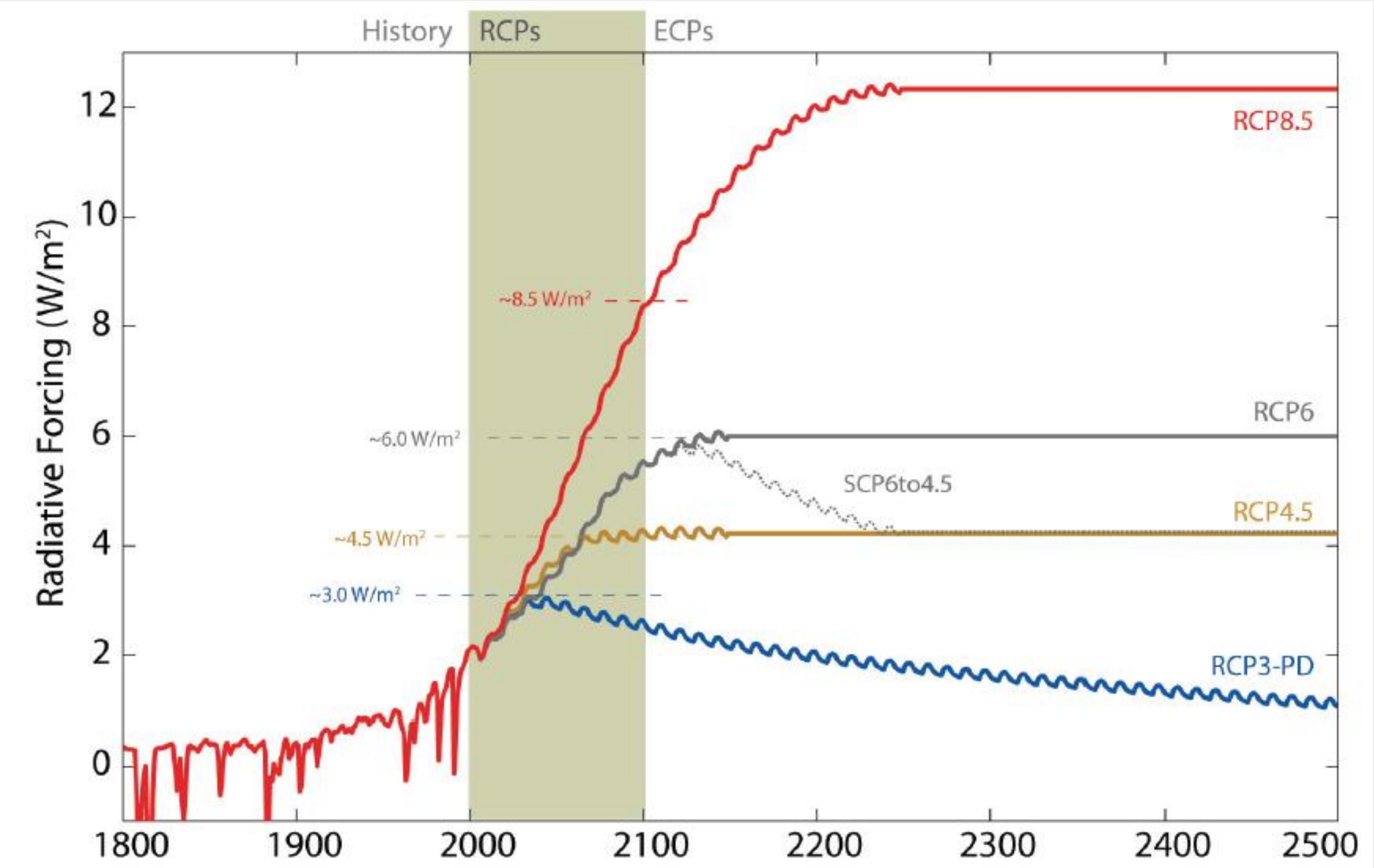


Global Fossil CO2 Emissions to 2300



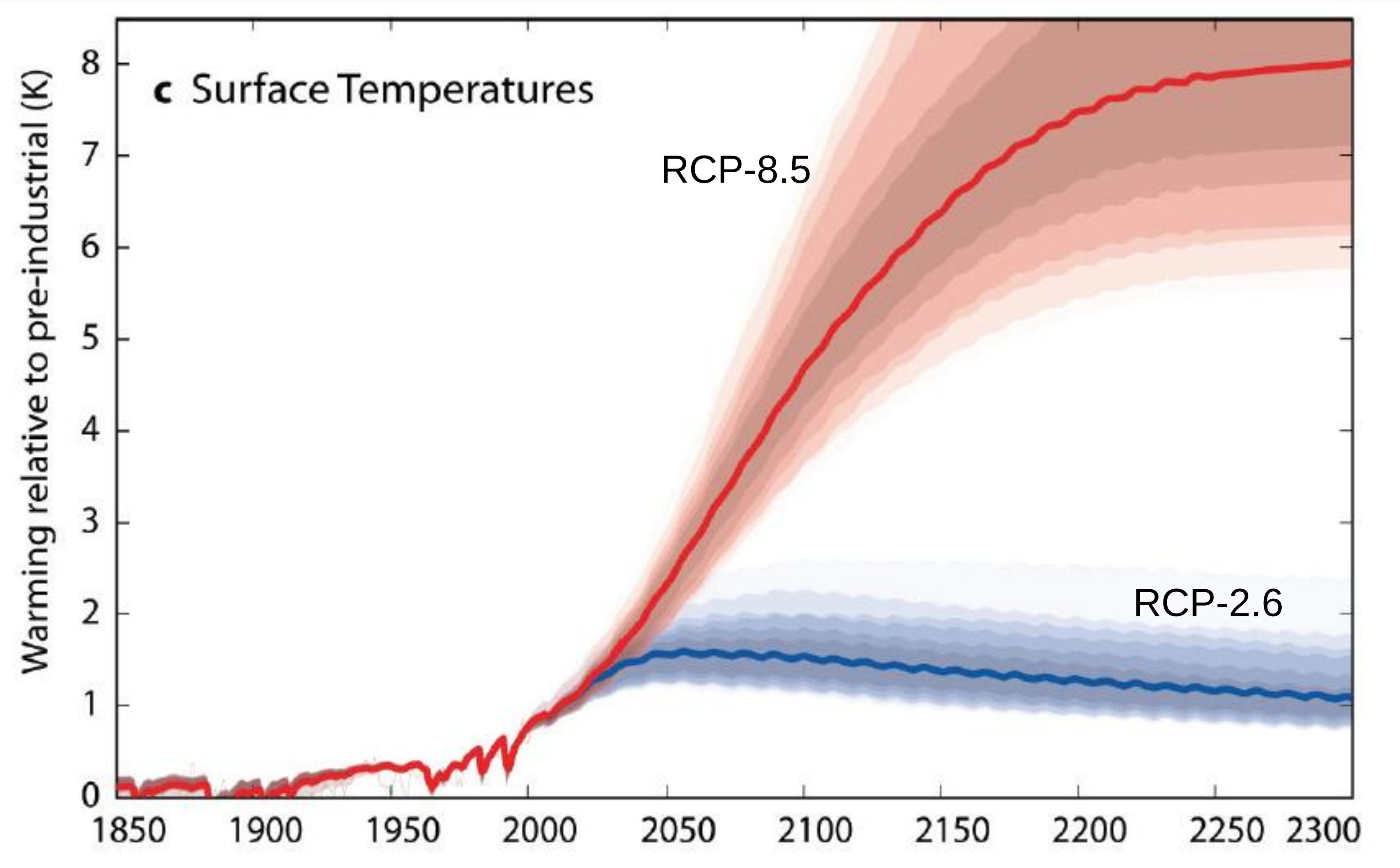
Source: RCP extensions from Meinshausen et al., submitted.

RCP radiative forcing



Source: Meinshausen et al., submitted.

RCP Temperature Projections



Source: Meinshausen et al., submitted.

Summary: Uncertainty ranges

- Overly narrow range of uncertainty in population and GDP over the entire time horizon, but especially in the long term
- Range of emissions through 2100 reasonably consistent with the range in the literature
- Range of emissions beyond 2100 higher than the range in the RCP extensions (although not clear that matters)

Issues

- **Current uncertainty ranges in literature may themselves be too conservative**
- **Structure of future economy in the long-term: what does a particular GDP/capita in 2300 mean?**
- **Regional distribution of people and production**
- **Catastrophic impacts: high emissions scenarios are lots of warming! Median of 8+ degrees by 2300**
- **Do current damage functions apply even approximately to conditions in the very long term?**
  – How relevant would a damage function created in 1700 be to measuring climate damages today?

Recommendations

- **Demonstrate key sources of uncertainty, including the contribution to SCC from different time periods**
- **Drop the use of a range of best estimates**
  - “single scenarios” are used for extensions beyond 2100, when uncertainty is greatest
- **Consider a substantially wider range of socio-economic futures, through 2100 and 2300**
- **Consider simpler approaches to damages in very long term: generic sectors and damage types**
- **Improve how uncertainty in results is characterized**
  - Use of probabilistic terms for SCC results is problematic when only sub-components are quantified (i.e., results are highly conditional)
- **Consider linking to evolving work on RCPs and socio-economic scenarios that are consistent with them**

Knowability and no ability in climate projections

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Seattle, WA

1. Introduction

The purpose of this note is to provide a referenced summary of the present scientific understanding about future climate change, tailored towards the kind of global climate factors that are captured in Integrated Assessment Models (IAMs). In outline, it is organized as follows:

i) *Equilibrium climate sensitivity* is the long-term response of global temperature to a doubling of atmospheric CO_2. I review the causes of our current uncertainty, and the prospects for reducing it.

ii) Two other measures of climate change are arguably more important in this context. First the *climate commitment* is a measure of the climate change we already face because of emissions that have already occurred.

iii) The very long timescales associated with attaining equilibrium, especially at the high end of possible climate sensitivity, mean that the *transient climate response* is of greater relevance for climate projections over the next several centuries.

iv) Due to the inherent uncertainties in the climate system, a *flexible emissions strategy* is far more effective in avoiding a given level of global temperature change, than a strategy aims to stabilize CO_2 at a particular level.

v) Many important climate impacts are fundamentally regional in nature. Among climate models, regional climate projections correlate only partially with global climate projections.

This was prepared for the EPA Climate Damages Workshop, Washington, D.C., Nov 18-19, 2010.

2. Climate sensitivity

Climate sensitivity (here given the symbol T_{2x}, and sometimes called the equilibrium climate sensitivity) is the long-term change of annual-mean, global-mean, near-surface air temperature in response to a doubling of carbon dioxide above preindustrial values. It has long been a metric by which to compare different estimates of the climate response to greenhouse gas forcing (e.g., Charney, 1979). There is a vast literature that has researched climate sensitivity from every possible angle, ranging from state-of-the-art satellite observations of Earth's energy budget, to geological studies covering hundreds of millions of years. A fine review of where things stand can be found in Knutti and Hegerl (2008).

Figure 1 shows a variety of probability distributions (pdfs) of climate sensitivity. A prominent feature of such estimates is that they all exhibit considerable skewness. In other words, while the lower bound is confidently known, the upper bound is much more poorly constrained. There is a small but nontrivial possibility (about 25 %) that the climate sensitivity could exceed 4.5 ^{o}C. One concern that has been raised is that the current generation of IPCC climate models (from the fourth assessment, or AR4) does not span the range of climate sensitivity that is allowable by observations (the blue histogram in figure 1 clusters too narrowly around the modes of the other pdfs). The reason for this appears to be that the IPCC climate models do not sample the full range of possible aerosol forcing (Armor and Roe, 2010). This should not be surprising since they are designed to represent the "best" estimate of climate (something akin to the mode of the distribution). However, since these computer models are the only tools available for modeling regional climates, it should perhaps be a concern that they are under sampling the range of possible futures. I next outline briefly how estimates are made from observations and models. The purpose of doing so is to straightforwardly demonstrate the important sources of uncertainty.

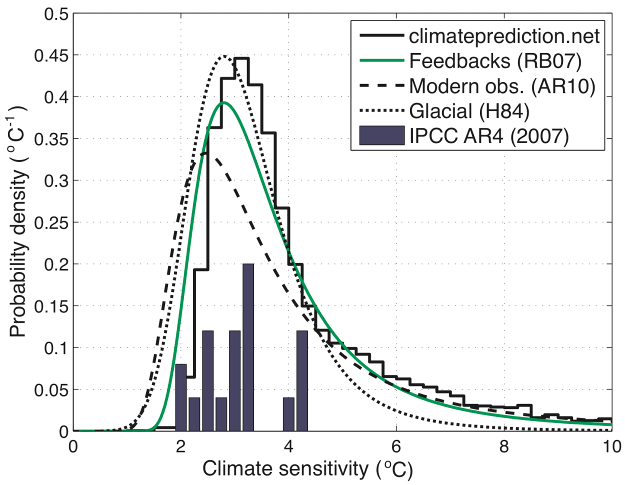

Figure 1. Various estimates of climate sensitivity. In order of the legend: i) from multi-thousand ensembles from one climate model (Stainforth et al., 2005), ii) from feedbacks with climate models (Roe and Baker, 2007), iii) from modern observations (Armour and Roe, 2010), iv) from glacial climates (Hansen et al., 1984), v) A histogram of T_{2x} from 19 main IPCC AR4 models (IPCC, 2007).

2a. Estimates of climate sensitivity from observations.

A linear approximation of the Earth's energy budget is

$$R = H + \lambda^{-1} T, \tag{1}$$

where R is the radiative forcing (units W m^{-2}), H is the heat going into the world's oceans and being stored there, and $\lambda^{-1}T$ is the climate response in terms of the global-mean, annual-mean, near-surface air temperature T, and the climate sensitivity parameter, λ. (e.g., Roe, 2009, Armour and Roe, 2010, and many others). For silly historical reasons the terminology here can be confusing. λ is a more fundamental measure of climate system than T_{2x}, since it does not depend on any particular forcing. λ and T_{2x} are related in the following way. Let R_{2x} be the radiative forcing due to a doubling of CO_2 over pre-industrial values (≈ 4 W m^{-2}). In the long-term equilibrium, ocean heat uptake goes to zero, and so the climate sensitivity is just:

$$T_{2x} = \lambda R_{2x} \quad (2)$$

The point of this algebra is to make it clear that the goal of estimating climate sensitivity from observations is the goal of estimating λ from Equation (1):

$$\lambda = \frac{T}{R - H} \quad (3)$$

We have observations of T, R, and H, whose probability distributions are shown in figure 2. Hereafter we refer to R-H as the climate forcing, since it is the net energy imbalance that the atmosphere must deal with. H and T are actually quite well constrained, as is the radiative forcing associated with CO_2 and other greenhouse gases. As is clear from figure, the major source of uncertainty is R and, in particular, the component of R that is due to aerosols (small airborne particulates that can be either liquid or solid).

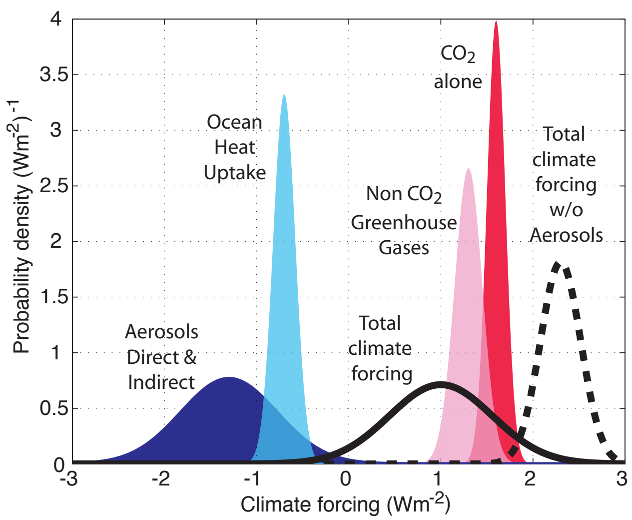

Figure 2: Probability distributions of the terms in the Earth's energy budget, based on IPCC 2007, and updated for newer ocean heat uptake observations. See Armour and Roe, 2010 for details. Total climate forcing is equal to R-H in Eq. 3. Also shown is the total forcing excluding aerosols, which is the climate forcing experienced by the Earth, if all anthropogenic emissions ceased immediately.

The reason that aerosol forcing is hard to constrain is that 1) the spatial pattern and lifetime is extremely complicated to observe (they are primarily in the Northern Hemisphere and downwind of major industrial economies); 2) some aerosols have a cooling effect, some have a warming effect; 3) aerosols alter the thickness, lifetime, and height of clouds – a powerful indirect effect that is hard to measure and attribute properly. The community is confident, however, that the net aerosol effect is almost certainly negative. More information about aerosol uncertainties can be found in Menon (2004).

Thus, from Eqs. 2 and 3, the probability distribution of climate sensitivity comes from combining a relatively narrow distribution (the well-known temperature change) in the numerator with a relatively broad distribution (the much less well-known climate forcing (i.e., R-H)) in the denominator of Eq. 3. It is this combination that produces the skewed distribution seen in figures 1 and 3c. The graphs in figure 3 are the fundamental reason why we can say with great confidence that it is very likely that observed forcing has not been large enough to imply a climate sensitivity of less than about 1.5 ^oC. On the other hand, uncertainties in observed forcing also mean that we cannot confidently rule out the disconcerting possibility that the modern warming has occurred with small climate forcing, which would imply very high climate sensitivity. Note that the curves in figure 1 and 3 are consistent with the probabilities given in the 2007 IPCC report.

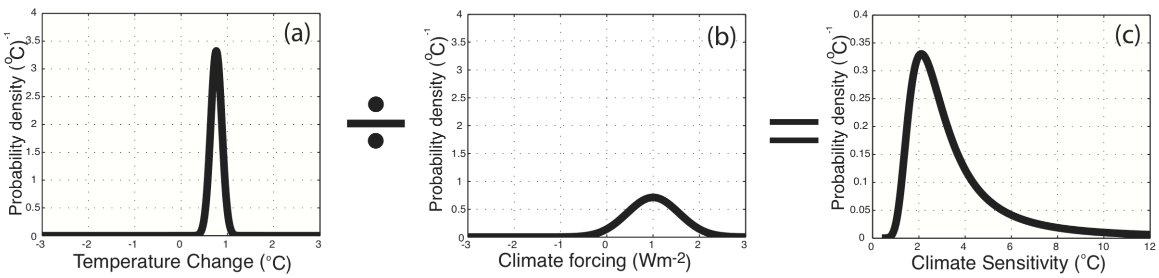

Figure 3: The calculation of climate sensitivity from observations involves combing a relatively narrow probability distribution of T (panel a) in the numerator, with a relatively broad distribution of F= H-R (panel b) in the denominator of Eq. (3). This leads to the skewed distribution of climate sensitivity (panel c). Note the pdfs must be combined properly - it is not just a simple division - but the point is hopefully clear.

2b. Estimates of climate sensitivity from models.

Climate sensitivity also can be estimated from climate models. Figure 1 shows three such efforts. The first is the spread of T_{2x} among the main IPCC AR4 models. One issue is that the mainstream IPCC AR4 climate models are not designed to explore the edges of the probability distribution, but instead are designed with the most likely combination of model parameters, and parameters are 'tuned' to reproduce observed climate history. Clear evidence of that tuning comes from the correlation of climate sensitivity and imposed aerosol forcing in the models in such a direction that twentieth century observations tend to be reproduced (Kiehl, 2007, Knutti, 2008). Such tuning is not problematic if models are interpreted as reflecting combinations of climate sensitivity and aerosol forcing that are consistent with observed constraints (Knutti, 2008). However AR4 models do not fully span the range of aerosol forcing allowed by observations (Kiehl, 2007; IPCC, 2007). This is the likely reason that the AR4 models under sample of the full range of possible climate sensitivity, as seen in figure 1.

Climate sensitivity can also be estimated by using thousands of integrations of the same climate model with the parameters varied by reasonable amounts, a strategy pursued by the *climateprediction.net* effort (figure 1, e.g., Stainforth et al., 2005). This work also found a skewed pdf of T_{2x}. Roe and Baker (2007) explain this in terms of a classic feedback analysis, summarized in figure 4. The relationship between feedbacks and response also produces a skewed distribution because of the way that positive feedbacks have a compounding effect on each other (e.g., Roe, 2009). The range of feedbacks as diagnosed within the AR4 models produces a pdf of climate sensitivity that is quite consistent with the pdf estimated from observations (figure 1). This should be expected since it is observations that ultimately provide constraints on the models.

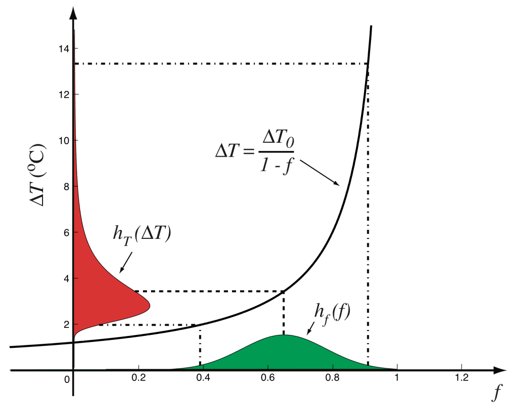

Figure 4: Model feedbacks and climate sensitivity. The black curve shows the mapping between climate feedbacks (x-axis, green curve), and climate response (y-axis, red curve). See Roe and Baker, 2007 for details.

2d. Prospects for improved estimates of climate sensitivity.

Can a narrower range of climate sensitivity be expected soon? One can ask: how might more accurate observations or better climate models change the estimate of T_{2x}?

Reducing uncertainty in either forcing or feedbacks would produce a narrower range. However it is the nature of these skewed distributions that the mode of T_{2x} moves to higher values as the range of forcing or feedbacks is narrowed, leaving the cumulative probability of $T_{2x} > 4.5^oC$ stubbornly persistent (Allen et al., 2007; Roe and Baker, 2007; Baker et al., 2010).

It should also be made clear that there are formidable scientific challenges in reducing uncertainty in climate model feedbacks, or in observing the aerosol forcing better. Progress will occur, but it is likely that it will be incremental.

Another line of attack is to try to combine multiple estimates of climate sensitivity in a Bayesian approach that might, in principal, significantly slim the fat tail of T_{2x} (e.g., Annan and Hargreaves, 2006). However, as with all Bayesian estimates, the value of the analysis is critically sensitive to 1) the independence of different observations; and 2) structural uncertainties within and among very complex models (e.g., Henriksson et al., 2010; Knutti et al., 2010). An objective assessment of these factors has proven elusive, rendering the information obtained by the exercise hard to interpret, and there is an acute risk that it produces overconfident estimates.

Overall it is probably prudent to anticipate that there will not be dramatic reductions in uncertainty about the upper bound on climate sensitivity (Knutti and Hegerl, 2008). On the timescale of several decades, Nature herself will slowly reveal more of the answer. We will learn about the transient climate response (see below) more quickly than the equilibrium climate sensitivity.

Those interested in understanding the above arguments in greater depth would do well to read the work of Prof. Reto Knutti (at ETH in Switzerland) and his collaborators. His research is of extremely high caliber, and quite accessible for a non-specialist.

3. The climate commitment.

What if all human influence on climate ceased overnight? Such a scenario—called the *climate commitment*—informs us of the climate change we already face due only to past greenhouse gas emissions. Framing the question this way has proven to be useful in providing a conceptual lower bound on future climate warming.

Early definitions of the climate commitment simply fixed CO_2 concentrations at current levels (e.g., Wigley, 2005; Meehl et al., 2005), but maintaining current levels actually requires continued emissions. Lately the focus has been more appropriately on the consequences of establishing zero emissions (e.g., Solomon et al., 2009). Two important, though sometimes overlooked points should be made. Firstly the geological carbon cycle means that, although much of the anthropogenic CO_2 ultimately gets absorbed by the ocean, some fraction — about 25 to 40% — remains in the atmosphere for hundreds of thousands of years (e.g., Archer et al., 2009). Secondly aerosols, have a short lifetime in the atmosphere (days to weeks). Thus when human influence ceases, aerosols are

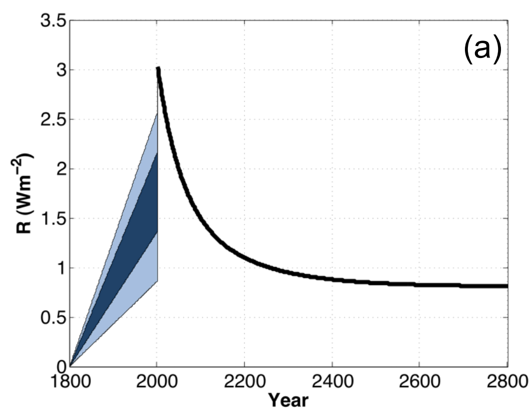

Figure 5: Idealized representation of the climate commitment following a cessation of all human influence on climate. Based on Armour and Roe, 2010. Panel (a) shows a simple view of how uncertainty in forcing has grown since 1800, as allowed by IPCC 2007 observed uncertainties. After emission cease (here at yr 2000) the uncertain aerosols quickly vanish, there is a jump in forcing due to sudden unmasking of the (relatively well-known) radiative forcing due to CO_2 and other greenhouse gases, which then declines slowly over time (black line). Panel (b) shows the temperature over this period, from a simple climate model. For each possible trajectory of past climate forcing history, a different value of climate sensitivity is implied, in order that the accurately known past warming is reproduced (low past forcing requires high climate sensitivity, and vice versa). The light blue curve shows the 90% confidence range, as permitted by uncertainties in observations, which ultimately grows to be 0.3 to 6°C at equilibrium. The dark blue curve is the `likely' IPCC range (68%). It is this range that is spanned by the main IPCC AR4 models because they under sample the allowed range of past forcing. Note that these calculations here only include uncertainties due to aerosols. The spread would be larger if uncertainties in GHG and ocean heat uptake were included. Nonetheless the graph highlights that uncertainty in future temperatures is a result of uncertainty in past forcing.

rapidly washed out of the atmosphere and the effect of this is to unmask additional warming due to the much more slowly declining CO_2 (illustrated in figure 2 and 5).

Figure 5 shows an idealized calculation of the climate commitment from Armour and Roe (2010), which contains more details. The purpose of showing this is to highlight that our uncertainty about future temperature comes primarily from our uncertainty about past forcing. After ceasing all emissions, the degree and trajectory of future warming depends on the state of the current climate forcing. We face the disconcerting possibility that our ultimate climate commitment already exceeds 2 ^{o}C, because of our current inability to rule out that past warming occurred with relatively little climate forcing. In other words, the lower flank of the pdf of the past climate forcing distribution (figure 5a) controls the upper flank of the pdf of the future temperature response (figure 5b).

3a. Climate forcing and climate sensitivity are not independent.

Perhaps the most important point to emphasize for the application to integrated assessment models (IAMs) is that climate sensitivity and climate forcing are not independent of each other. For any projections made of the future, a starting point for the current climate forcing must be assumed. We are currently quite uncertain about what that starting point is. If aerosol forcing is strongly negative, there is a strong implication that climate sensitivity is high. If aerosol forcing is weak, climate sensitivity must be low. Uncertainties in climate forcing and climate sensitivity must not be assumed to be independent.

4. The transient climate response.

Equilibrium climate sensitivity relates to a hypothetical distant future climate after the system has equilibrated to a stipulated forcing. The transient climate response over the course of a few centuries may be a more directly useful property of the climate system. A formal definition of the transient climate sensitivity has been proposed as the global-average surface air temperature, averaged over the 20-year period centered on the time of CO_2 doubling in a 1% yr^{-1} increase experiment, which occurs roughly at 2070. While this metric may be more relevant for the future, a negative trade-off is that its exact value depends on this artificially defined trajectory of emissions.

For reasons discussed below, the transient climate response is much better constrained than climate sensitivity. In the words of the IPCC, it is very likely (> 9-in-10) to be greater than 1°C and very unlikely (< 1-in-10) to be greater than 3 °C. Thus the community is much more confident about the evolution of the climate over the coming century than it is about the ultimate warming.

4a. The immensely long timescales of high sensitivity climates.

A key factor in the long-term evolution of the climate is the diffusive nature of the ocean heat storage (figure 6b). In order to reach equilibrium the ocean abyss must also warm, and because of the relatively sluggish circulation of the deep ocean, the upper layers must be warmed before the lower layers, and the more the temperature change must be, the longer diffusion takes to work. A simple scaling analysis (e.g., Hansen et al., 1985) shows that:

$$\text{Climate adjustment time} \propto (\text{climate sensitivity})^2$$

Thus if it takes 50 yrs to equilibrate with a climate sensitivity of 1.5 °C, it would take 100 times longer, or 5,000 yrs to equilibrate if the climate sensitivity is 15 °C. Although Nature is of course more complicated than this, the basic picture is reproduced in models with an (albeit simplified) ocean circulation. Figure 6a shows one such calculation from Baker and Roe (2009), though there are others (in particular see Held et al., 2010).

If IAMs are to be used to project out more than a few decades, it is critical that they represent this physics correctly. A single adjustment time for climate, or a deep ocean that is represented as a uniform block, cannot represent this behavior.

The extremely high temperatures found in the fat tail of climate sensitivity cannot be reached for many centuries for very robust physical reasons. Failure to incorporate this fact will lead to a strong distortion of the evolution of possible climate states, and of the subsequent IAM analyses based on them.

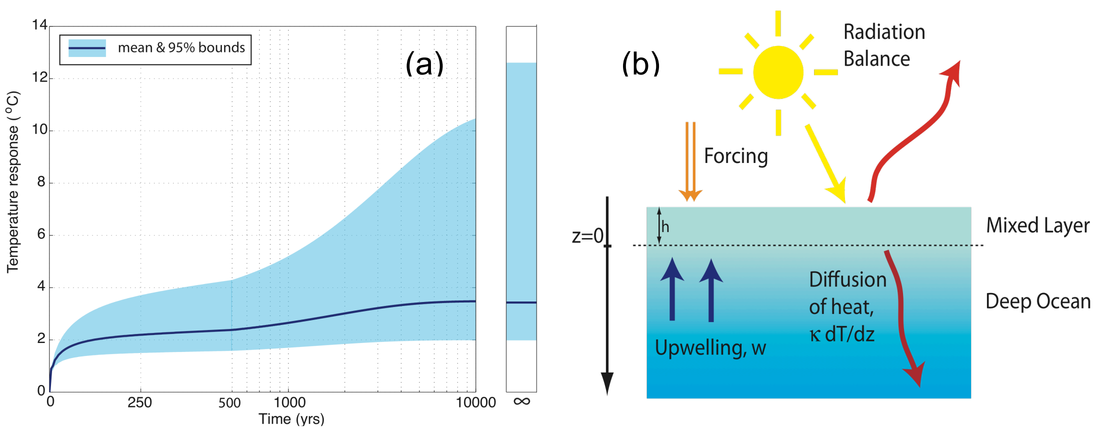

Figure 6: (a) The evolution of possible climate trajectories in response to an instantaneous doubling of CO_2 given the existing uncertainty in climate sensitivity. From Baker and Roe, 2009. Note the change to a logarithmic x-axis after 500 years. Low climate sensitivity is associated with rapid adjustment times (decades to a century). High climate sensitivity has extremely long adjustment times – thousand of years. This results from the fundamentally diffusive nature of the ocean heat uptake, illustrated schematically in panel (b). Such behavior is also reproduced in more complete physical models. See Held et al. (2010), for example.

5. CO_2 stabilization targets are a mistake.

A prominent part of the conversation about action on climate change has centered on what the right level of CO_2 should be in the atmosphere (e.g., Solomon et al., 2010). Some advocate for 350 ppmv (e.g., Hansen et al. 2008), though we are already past 380 ppmv and climbing, others contemplate the consequences of 450 ppmv (e.g., Hansen, et al., 2007), still others 550 ppmv (Pacala and Soccolov, 2004; Stern, 2007).

However decreeing and setting in stone a particular target for CO_2 is fundamentally the wrong approach, and a vastly inefficient way to avoid a particular climate scenario. This point was made very elegantly and powerfully in a study by Allen and Frame (2007), reproduced in figure 7. Panel a) shows a scenario of what could happen if we decided today to stabilize CO_2 at 450 ppmv by 2100, and then waited for the climate to evolve. Our current best guess is that would lead to an equilibrium temperature change of 2 ^{o}C, taking us to the edge of what some have called dangerous climate change. However because of our current uncertainty in climate sensitivity, the envelope of possible climate states is quite broad by 2150. In other words, our hypothetical choice that we made today still leaves us exposed to a quite broad envelope of risk. Note, though, that figure 7a is consistent with figure 6 – temperatures in the fat tail of high climate sensitivity are still very, very far from equilibrium at 2150.

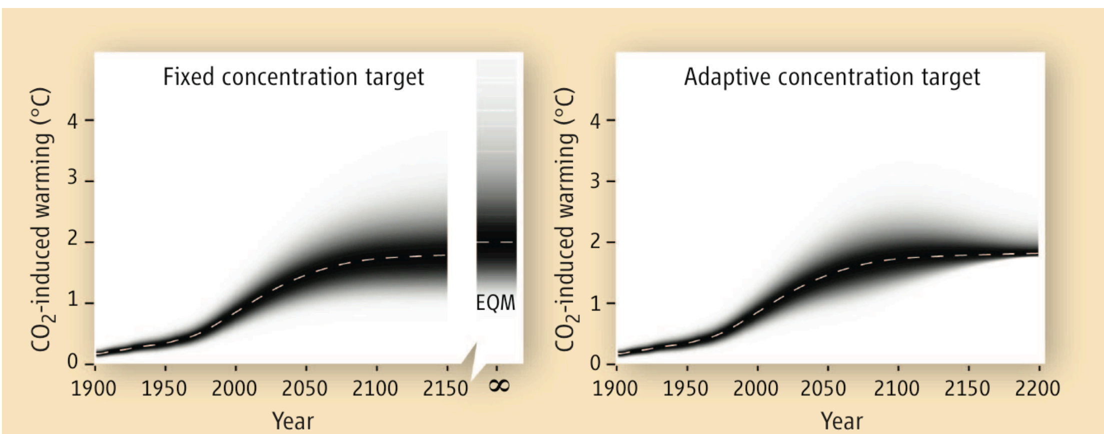

Figure 7: reproduced from Allen and Frame (2007). Carbon dioxide–induced warming under two scenarios simulated by an ensemble of simple climate models. (Left) CO_2 levels are stabilized in 2100 at 450 ppm; (right) the stabilization target is recomputed in 2050. Shading denotes the likelihood of a particular simulation based on goodness-of-fit to observations of recent surface and subsurface-ocean temperature trends. The darker the shading, the likelier the outcome.

Panel b) of figure 7 considers an alternative strategy in which we still act according to our best guess today, but re-compute a new concentration target at 2050, based on the fact that 40 years have elapsed and Nature has given us more information about what trajectory we are on. Figure 7b makes it clear that this adaptive strategy is vastly more effective in achieving a desired climate target (in this case a global temperature change of 2 ^{o}C).

Because the link between CO_2 levels and global temperature is uncertain, and because it is prudent to anticipate only incremental advances in our understanding, it is common sense to pursue a strategy that has built-in flexibility rather than declaring a fixed concentration.

6. How well do global projections correspond to regional projections?

Many of the most important climate impacts – changes in hydrology, storminess, heat waves, snowpack, etc. – are fundamentally regional in nature. How reliable is global climate change as a predictor of regional climate change? Since this is a question about the future, we are forced to use climate models. Figure 8 analyzes how well global climate sensitivity correlates with local climate change (in this case annual mean temperature and precipitation change in 2100), comparing among eighteen different IPCC models (IPCC, 2007).

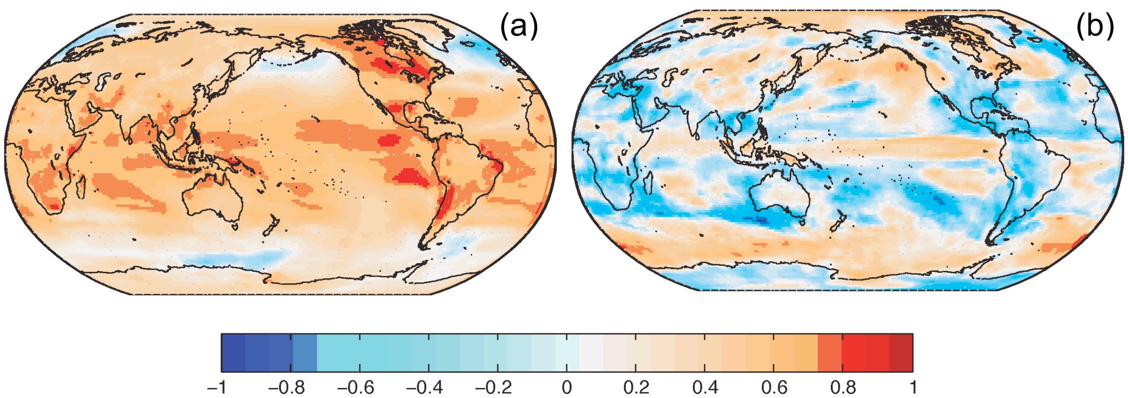

Figure 8: a) correlation among 17 IPCC climate models of their global equilibrium climate sensitivity and their local annual-mean temperature change in 2100,; b) same as a), but for annual-mean precipitation. Calculation made by N. Feldl from IPCC archived model output based on the A1B emissions scenario, and similar plots for other variables are at *http://earthweb.ess.washington.edu/roe/GerardWeb/Publications.html.*

It takes a correlation of $r \sim 0.75$ before half of the variance (i.e., r^2) of the local climate change is attributable to the global climate change. Only a very few patches of the planet achieve even this level of correlation in annual temperature (Figure 8a) and nowhere reaches this measure in annual precipitation (Figure 8b). This highlights that the connection between regional and global climate change is not that strong. This result should not be surprising: though models may all agree on the *sign* of the climate change in a given region, there is a great deal of scatter and individual model vagaries in projecting the *magnitude* of the climate change. Research into the limits of regional predictability is only just beginning. A useful starting point is Hawkins and Sutton (2009).

Summary.

1) The most important point to drive home is that uncertainty is not ignorance. The planet has warmed in the recent past, and will continue to warm for the foreseeable future. That this is a result of our actions is beyond rational dispute. The overwhelming preponderance of the IPCC 2007 report is extremely reliable,

and reflects an objective characterization of the best current understanding about climate. All of the following points are consistent with (and in many cases drawn from) that report.

2) A traditional measure of the planet's response, equilibrium climate sensitivity is uncertain, primarily because of uncertainty in the radiative forcing due to aerosols. This precludes us from calibrating our models of climate with greater accuracy.

3) However a focus on climate sensitivity may be misplaced because of the tremendously long timescales associated with reaching equilibrium – thousands of years in the case of the fat tail of high climate sensitivity.

4) If all human influence were to cease today, the rapid loss of anthropogenic aerosols from the climate would unmask CO_2 warming, and the planet's temperature would increase as a result. The degree of warming is quite uncertain.

5) For related reasons, a strategy that aims to stabilize concentration of greenhouse gasses at a particular level is a mistake, because the degree of warming is still unpredictable. A strategy that aims for a flexible emissions will be much more effective at preventing a particular level of warming.

6) IAMs have to make choices about how to represent climate forcing associated with human activity. We are quite uncertain about what this level is right now. It is crucial to appreciate that uncertainty in climate sensitivity and uncertainty in climate forcing cannot be treated as independent.

7) Many climate damages both to humans and to the biosphere result from regional climate factors. Unfortunately, there is relatively little agreement among climate models about how global climate changes relate to local climate changes, and this is especially true in some of the most vulnerable subtropical regions. Thus the meaning of analyses that use only global temperature changes to assign climate damages is unclear.

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Knowability and no ability in climate projections

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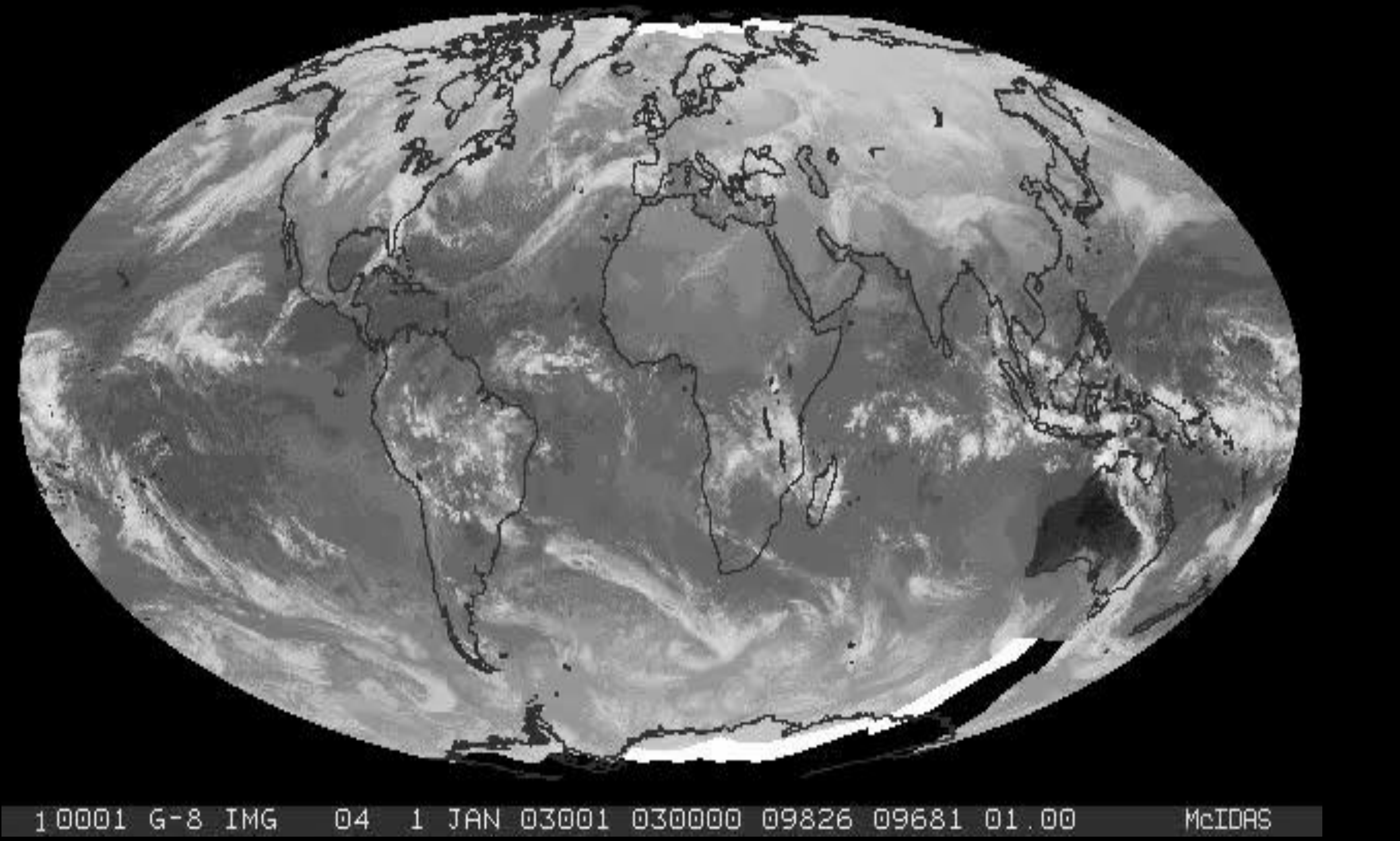
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How sensitive is climate to changes in CO_2?

A traditional measure

- *Climate sensitivity* *(or equilibrium climate sensitivity)*

> Definition: the long-term change in annual-mean, global-mean, near-surface air temperature to a doubling of CO_2 above preindustrial values
> (phew!, e.g., Arhenius, 1896, Charney, 1979)

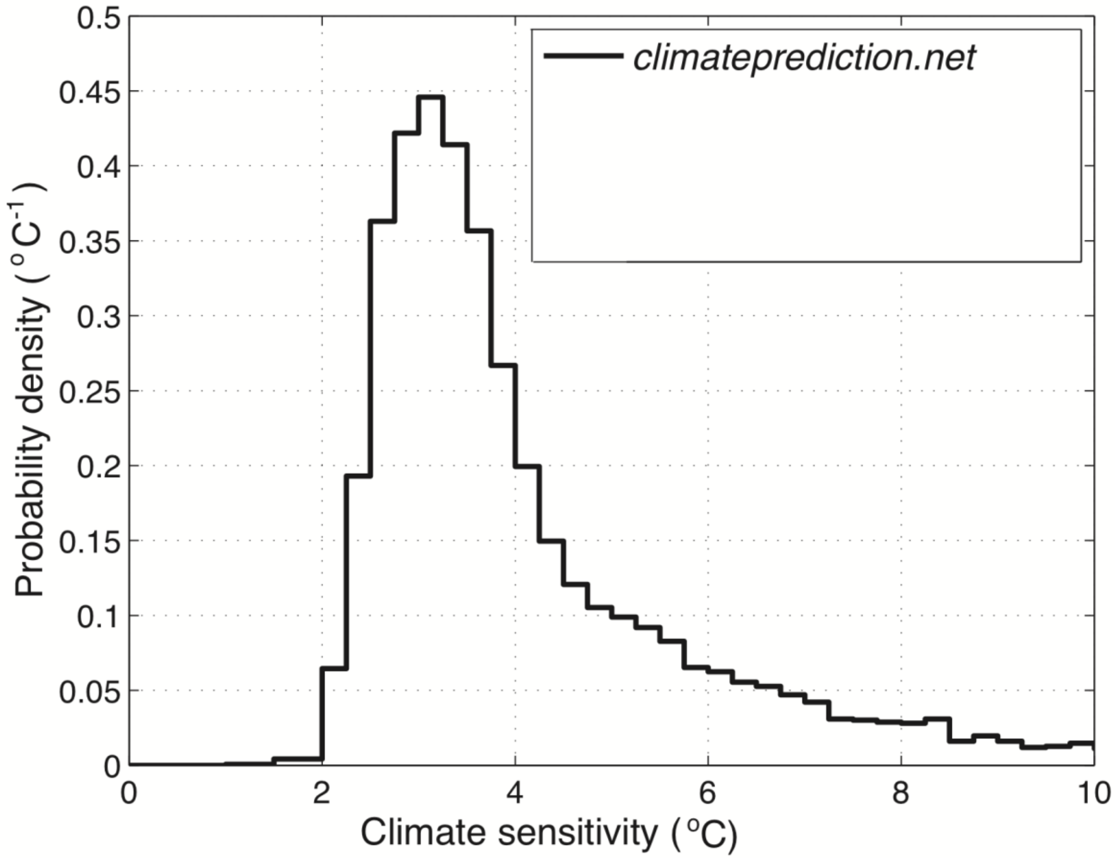
- IPCC 2007 says:

Likely (2-in-3)	$2.0 < \Delta T < 4.5^oC$
Very unlikely (<1-in-10)	$\Delta T < 1.5^oC$

- Note this leaves ~2-in-10 chance for $\Delta T > 4.5\ ^oC$
  (though IPCC says observations are less well fit with these values)

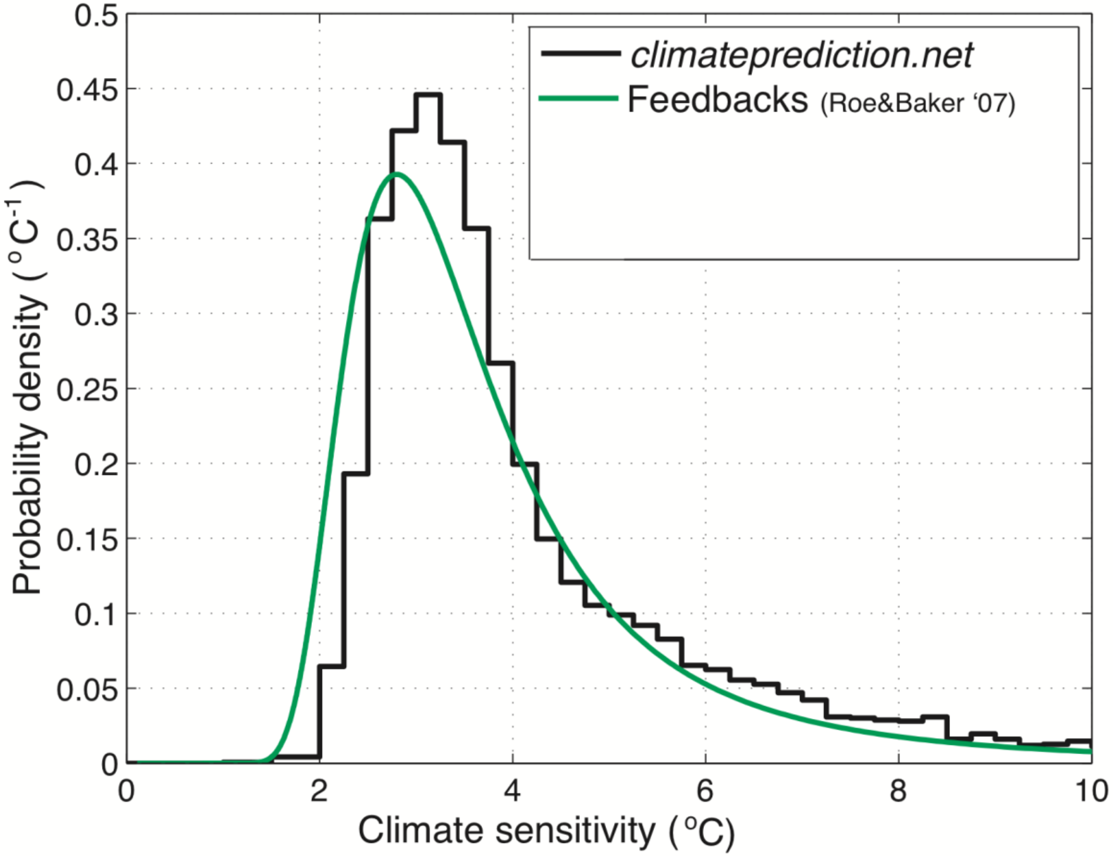
Climate sensitivity

1. Different estimates



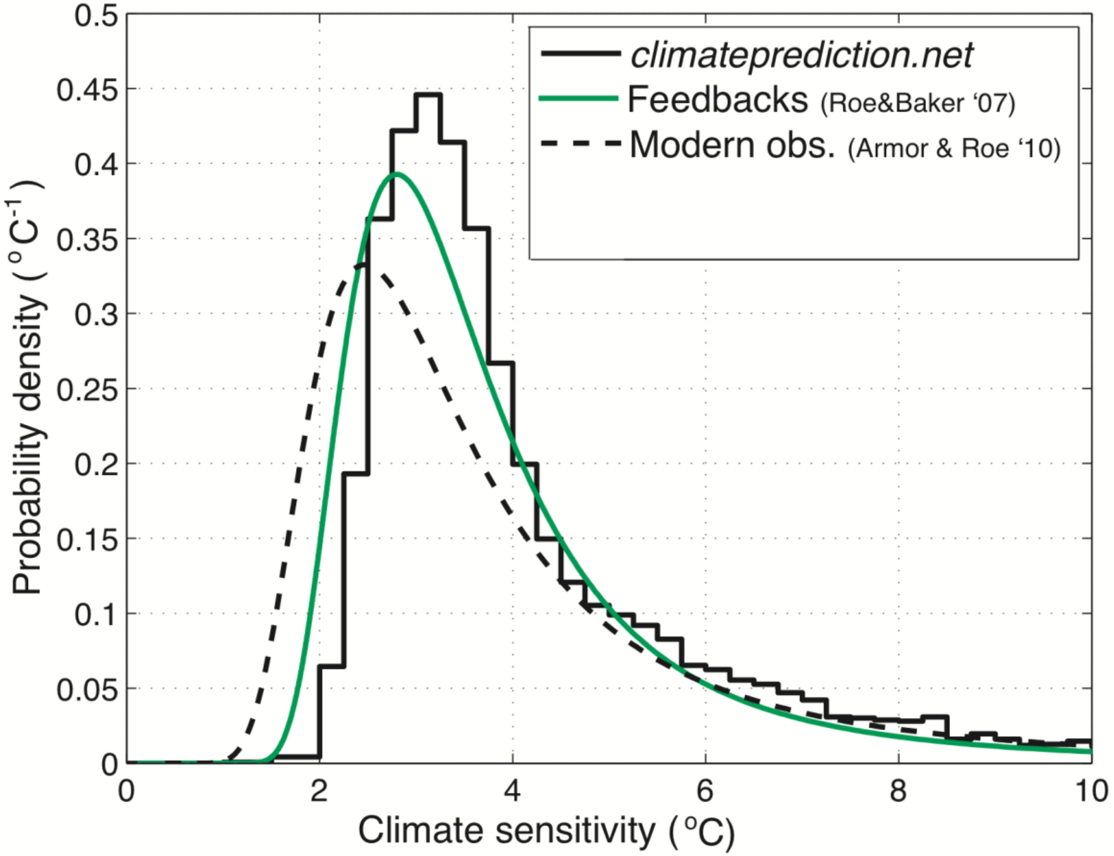
Climate sensitivity

1. Different estimates



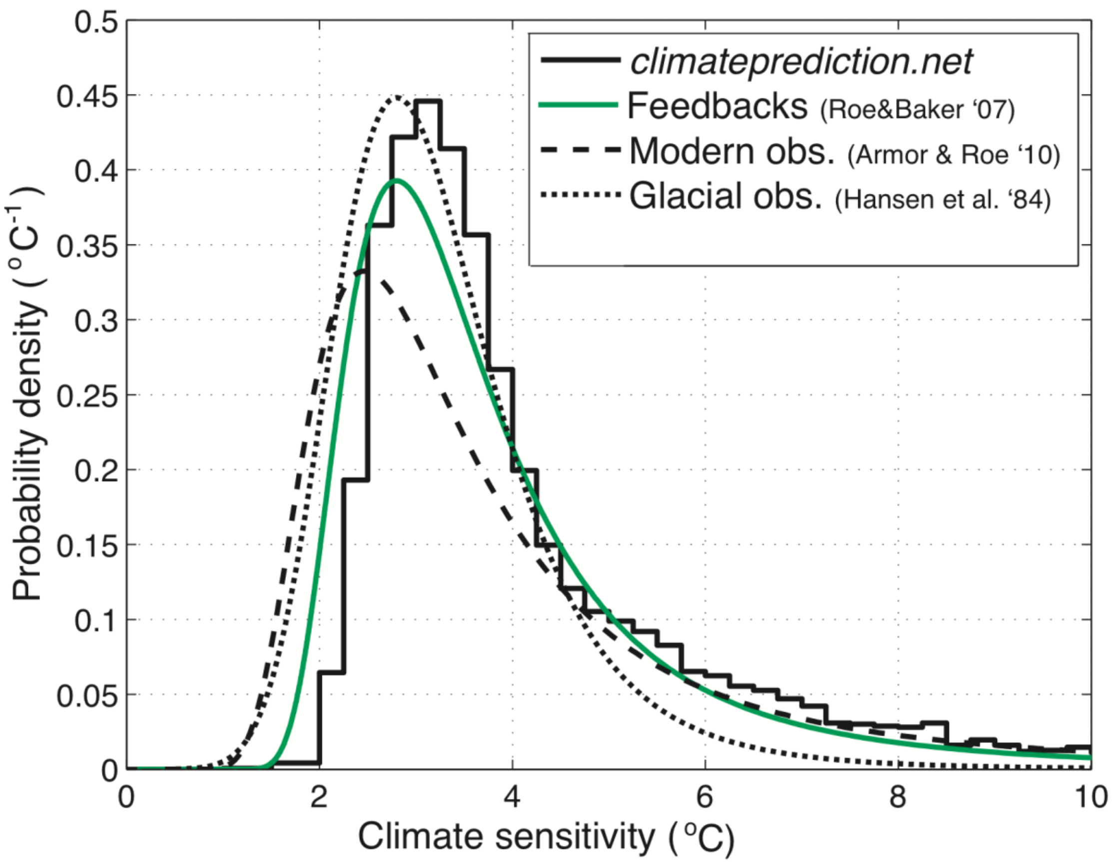
Climate sensitivity

1. Different estimates



Climate sensitivity

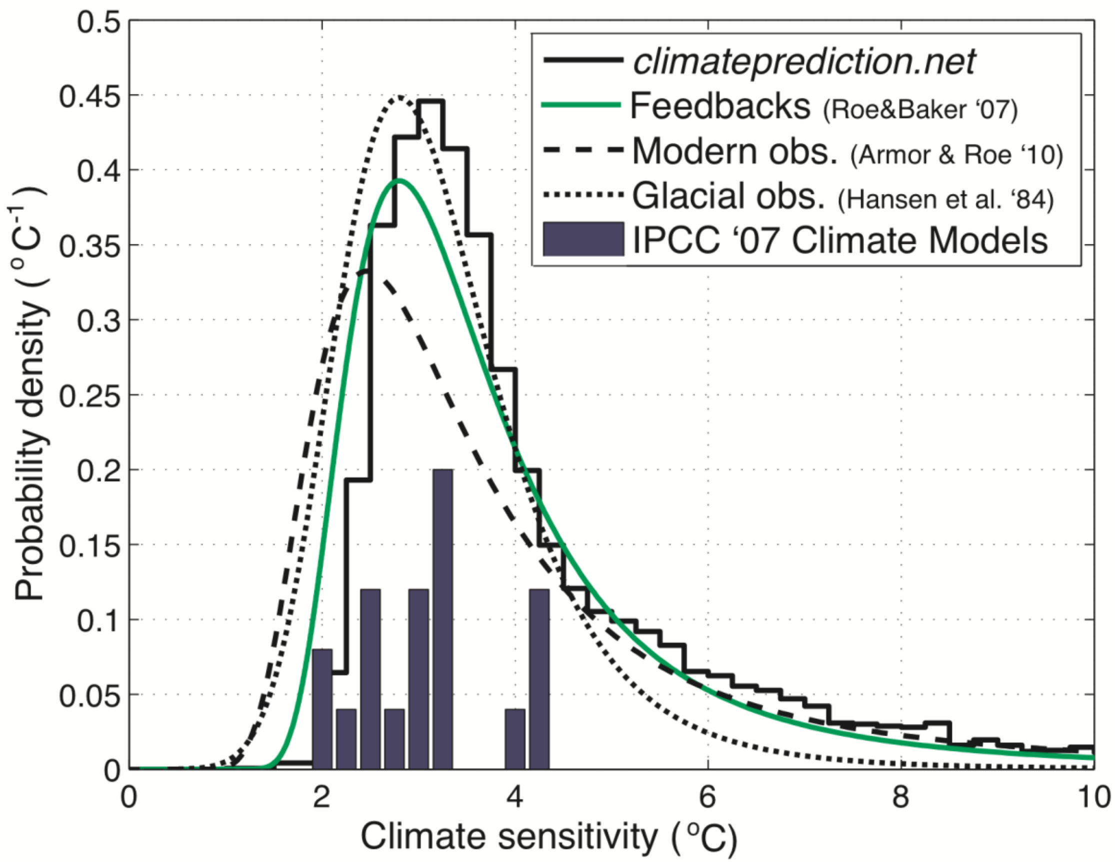
1. Different estimates



So why these values, and why this shape?

Climate sensitivity

1.5 An aside



- The main IPCC climate models under-sample the allowed range.
- An issue for regional climate predictions?

Climate sensitivity

2. Estimates from observations

Global energy budget:

$$R_f = F + \lambda^{-1} \Delta T$$

forcing = storage (ocean) + atmospheric response

In principle, get R_f, F, ΔT from observations, solve for λ, then:

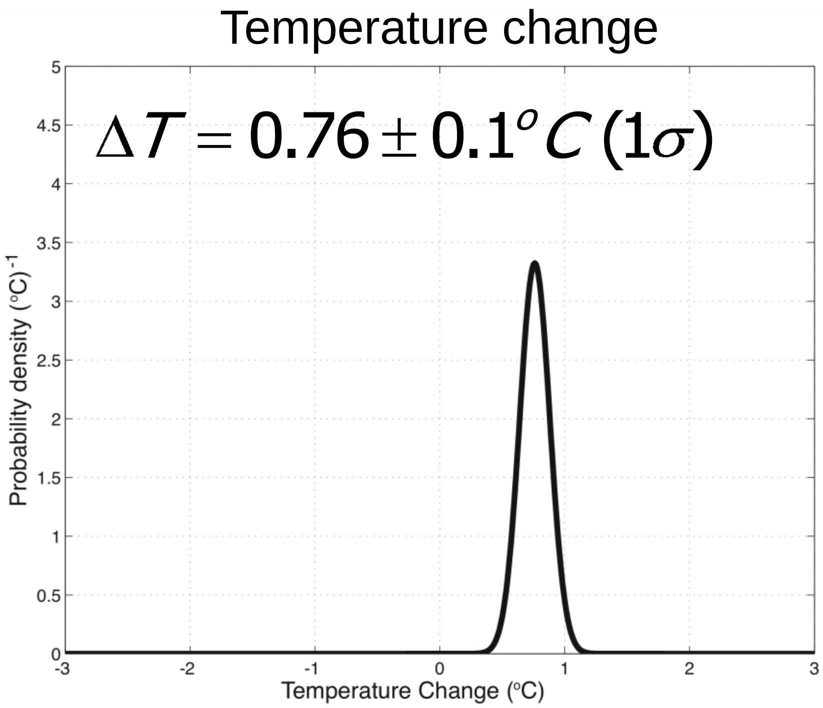
$$\Delta T_{2xCO_2} = \lambda \, R_{f\,2xCO_2}$$

$R_{f\ 2xCO2}$ ~4 W m^{-2}

Climate sensitivity

2. Estimates from observations

How much warming has there been since pre-industrial times?

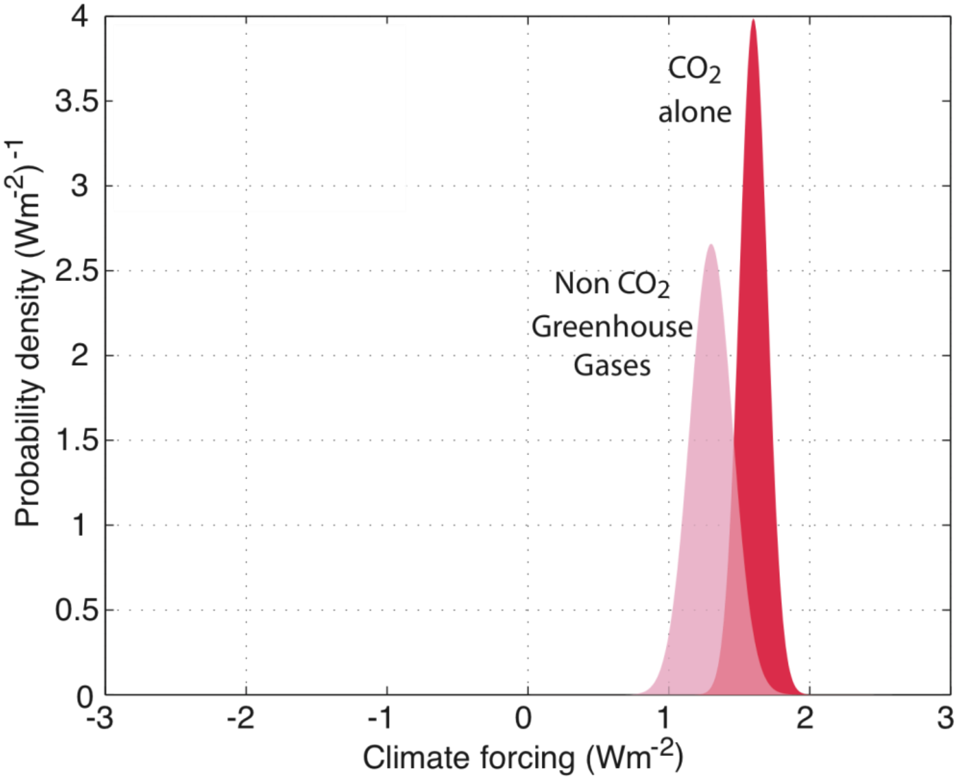


• Global mean temperature change is <u>well observed.</u>

IPCC, 2007

Climate sensitivity

2. Estimates from observations



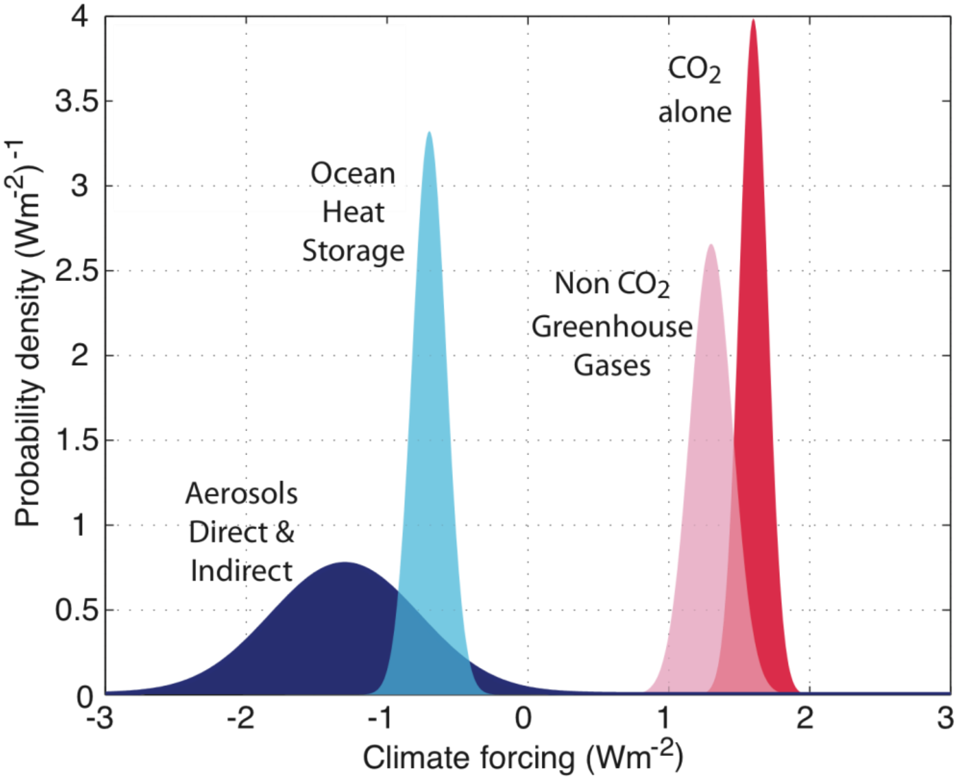
Numbers from IPCC, 2007

- Warming from CO_2 and other Greenhouse gases (CH_4, O_3)

  (plus a tiny bit from solar)

Climate sensitivity

2. Estimates from observations



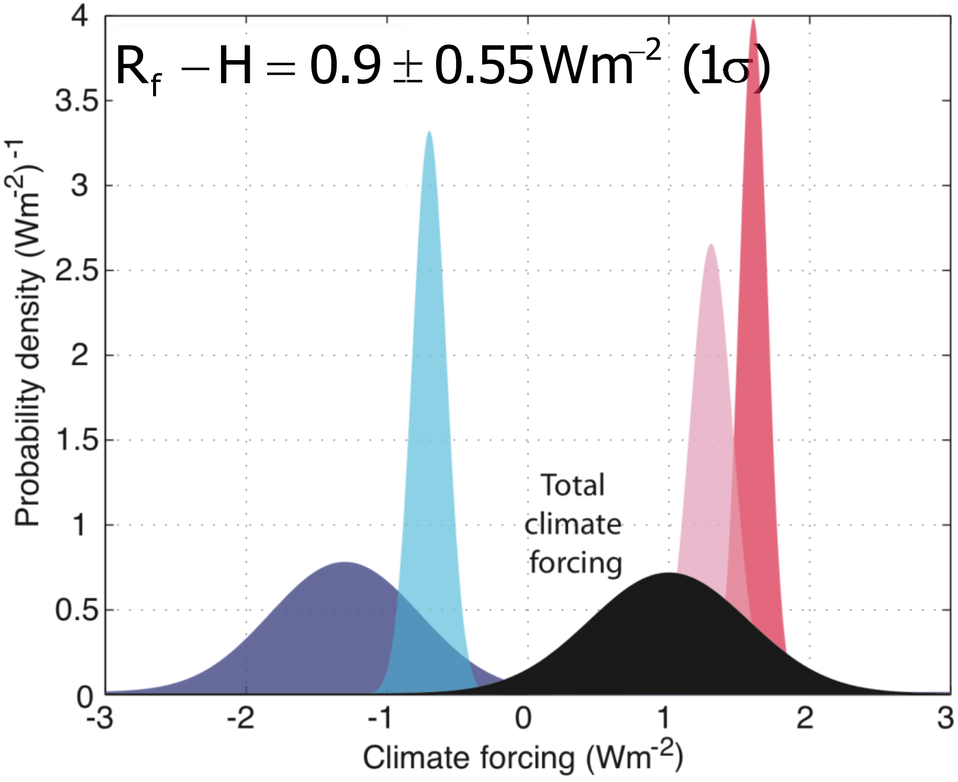
Numbers from IPCC, 2007 and Lyman et al. (2010)

- Cooling from heat storage in ocean, and aerosols

Aerosols: airborne particulates (solid/liquid)
have complicated effects (some warm, some cool, change clouds)

Climate sensitivity

2. Estimates from observations

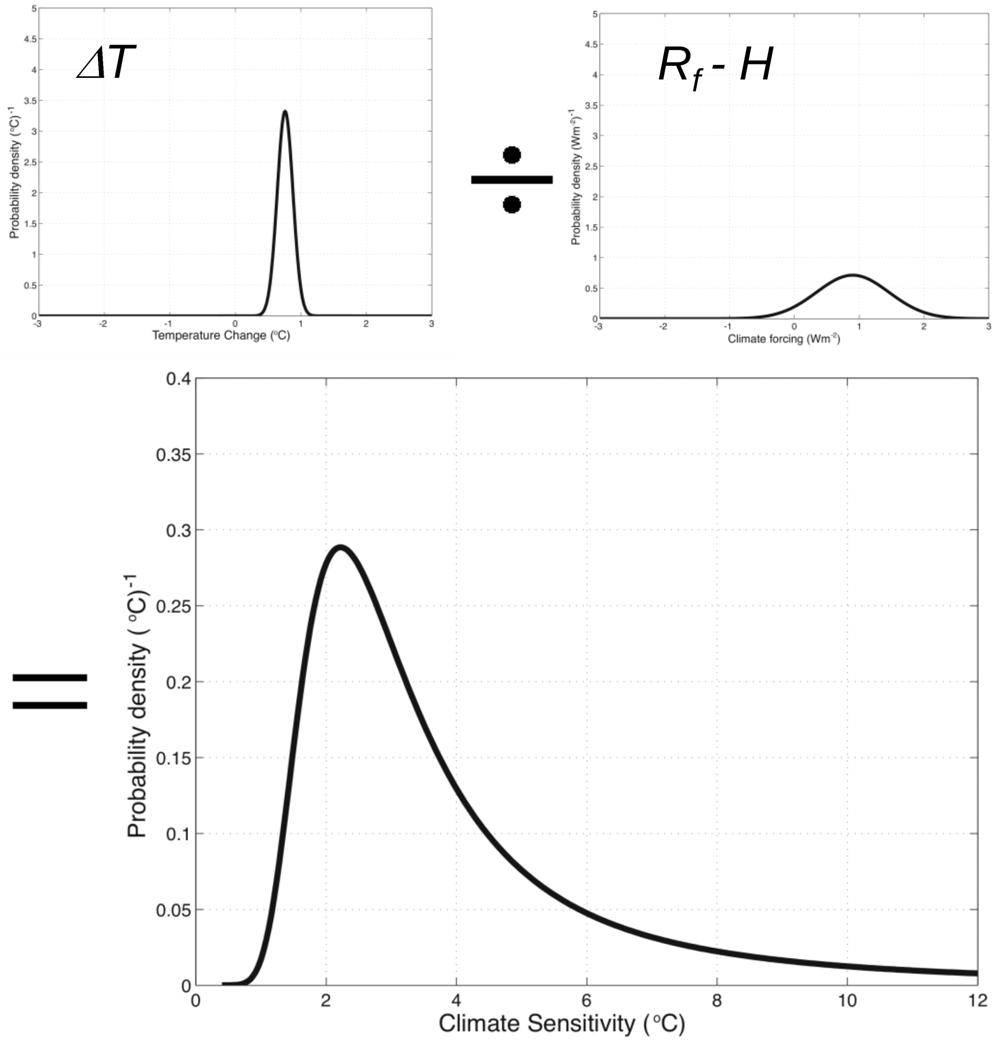


- Total climate forcing is <u>quite uncertain</u> and aerosols are the culprit.

Climate sensitivity

3. Estimates from observations

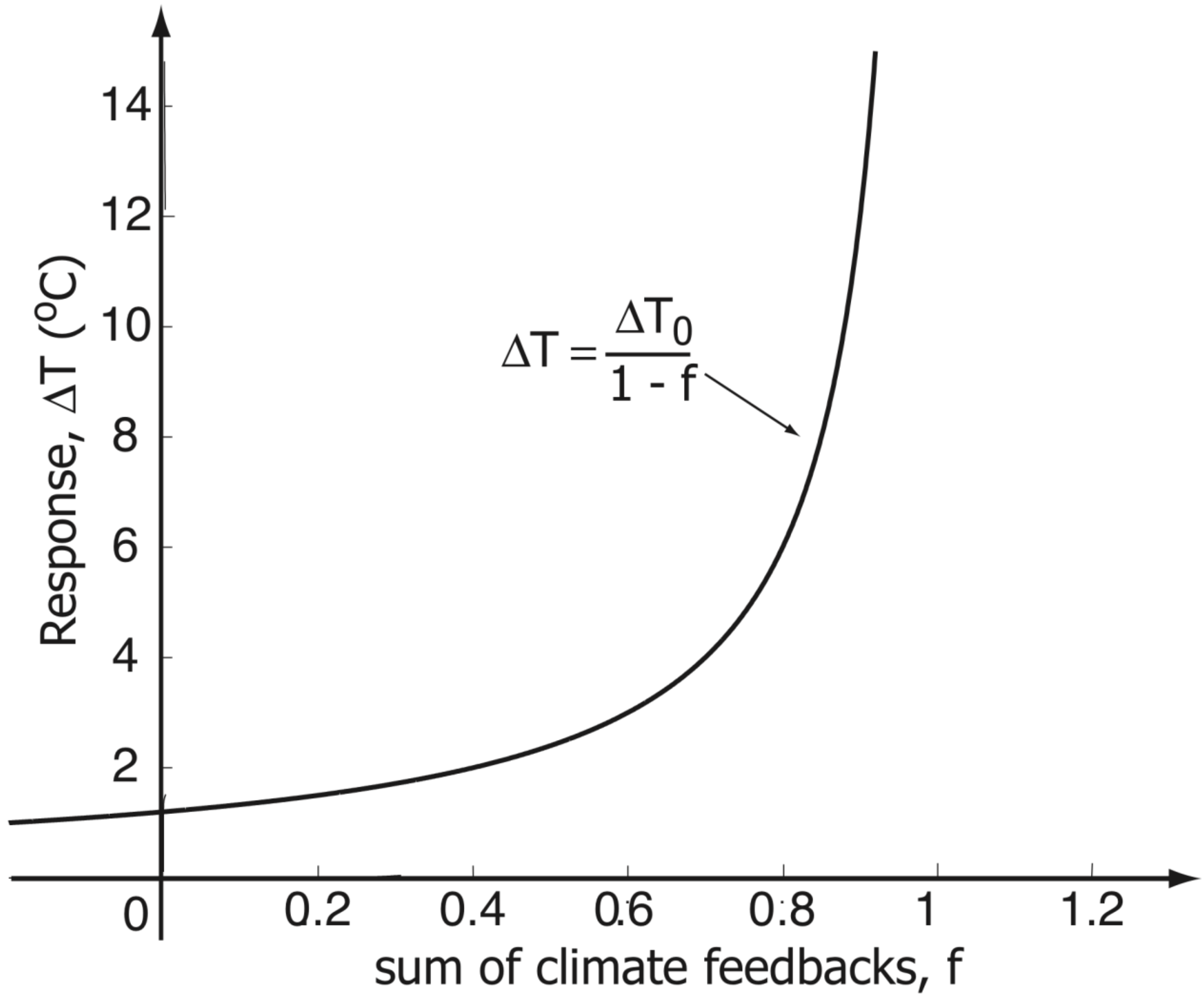
$$\lambda = \frac{\Delta T}{R_f - H}$$



- Fat tail is because aerosol forcing *could* be quite negative

Climate sensitivity

3. Estimates from models

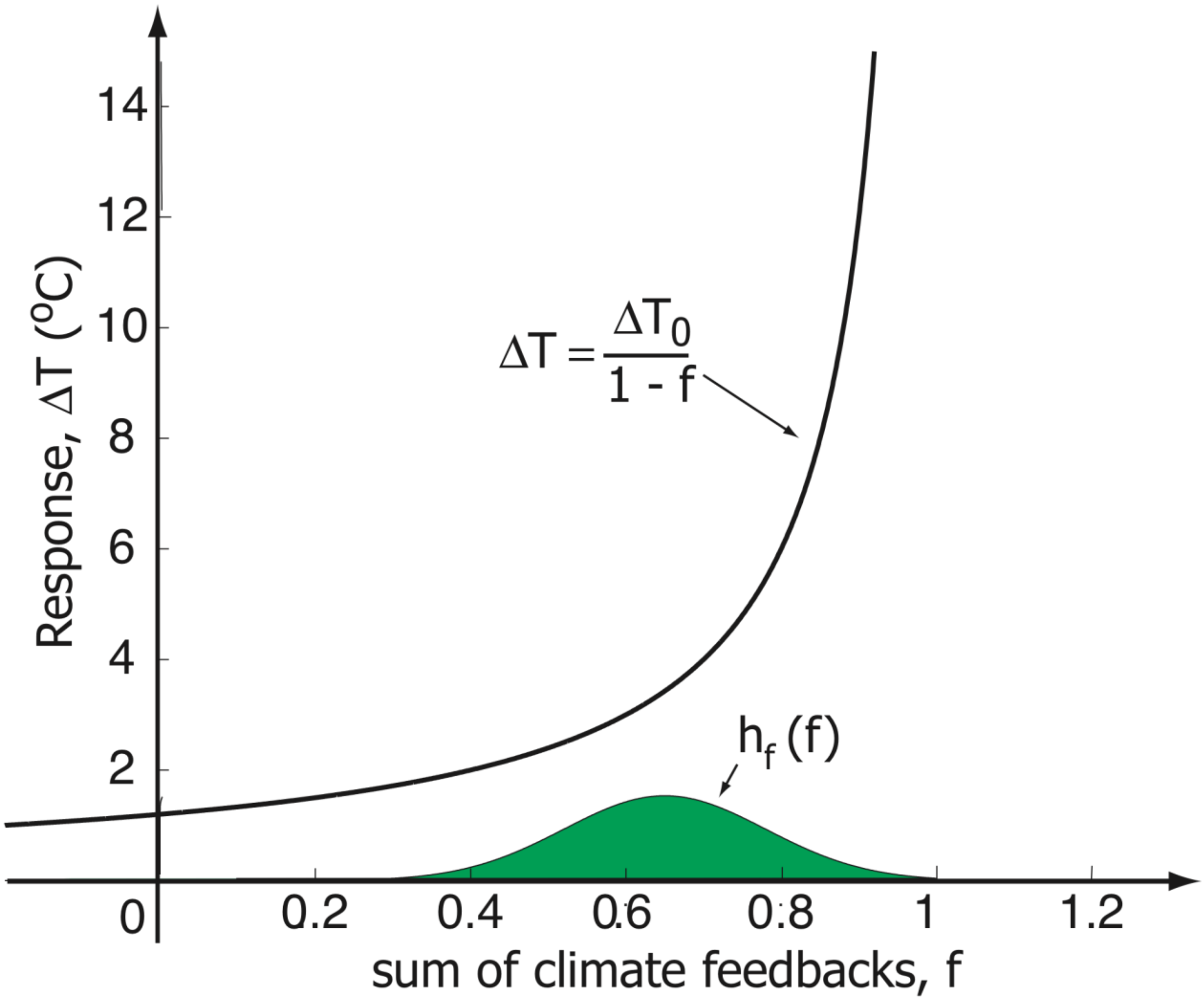


- Black curve is the relationship between climate feedbacks and climate sensitivity.

Roe & Baker, 2007

Climate sensitivity

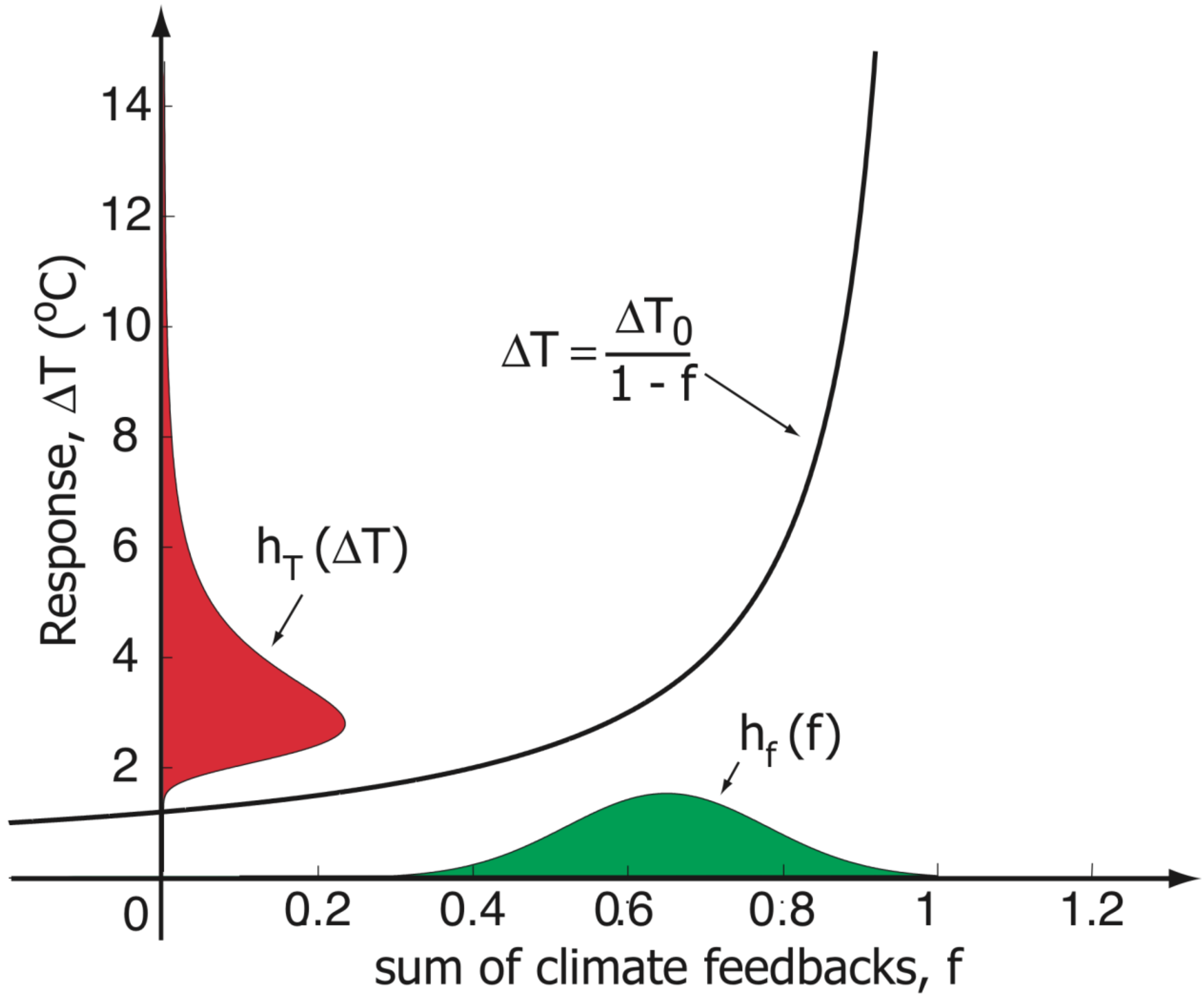
3. Estimates from models



- Green curve reflects current uncertainty in climate feedbacks.

Climate sensitivity

3. Estimates from models

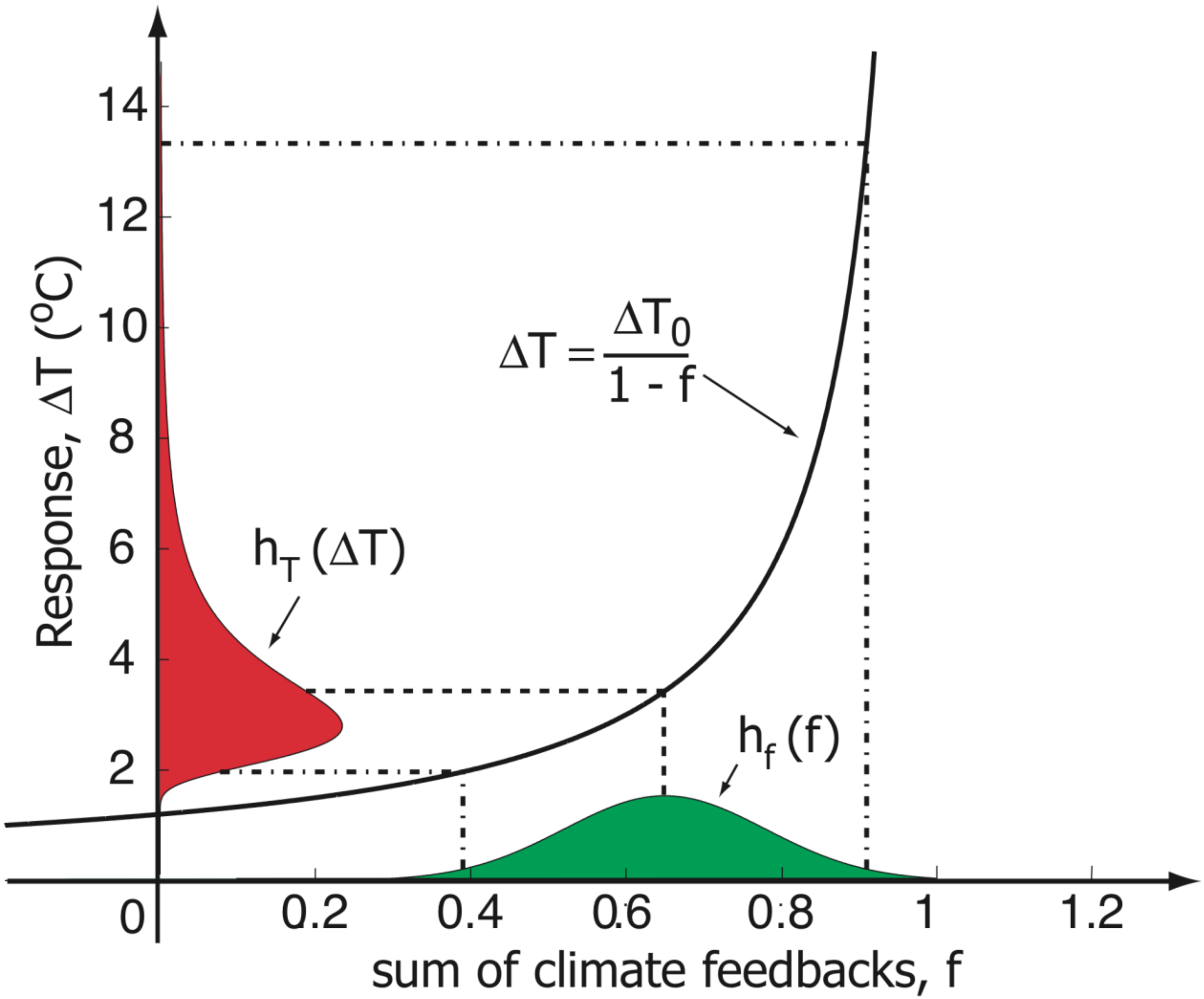


- Red curve is resulting uncertainty in climate sensitivity.

Roe & Baker, 2007

Climate sensitivity

3. Estimates from models



- Red curve is resulting uncertainty in climate sensitivity.

Climate sensitivity

4. Prospects for progress

a. Improved observations/models

Its hard!! Incremental improvements, but probably no breakthroughs.

b. Combine different estimates?

Very hard to establish the degree of independence of individual estimates. (see Knutti and Hegerl, 2008)

c. Use other observations?

(e.g., NH vs. SH; pole-to-eq. ΔT; seasonality, trop. water vapor)

Structural errors among models highly uncertain. (see Knutti et al, 2010)

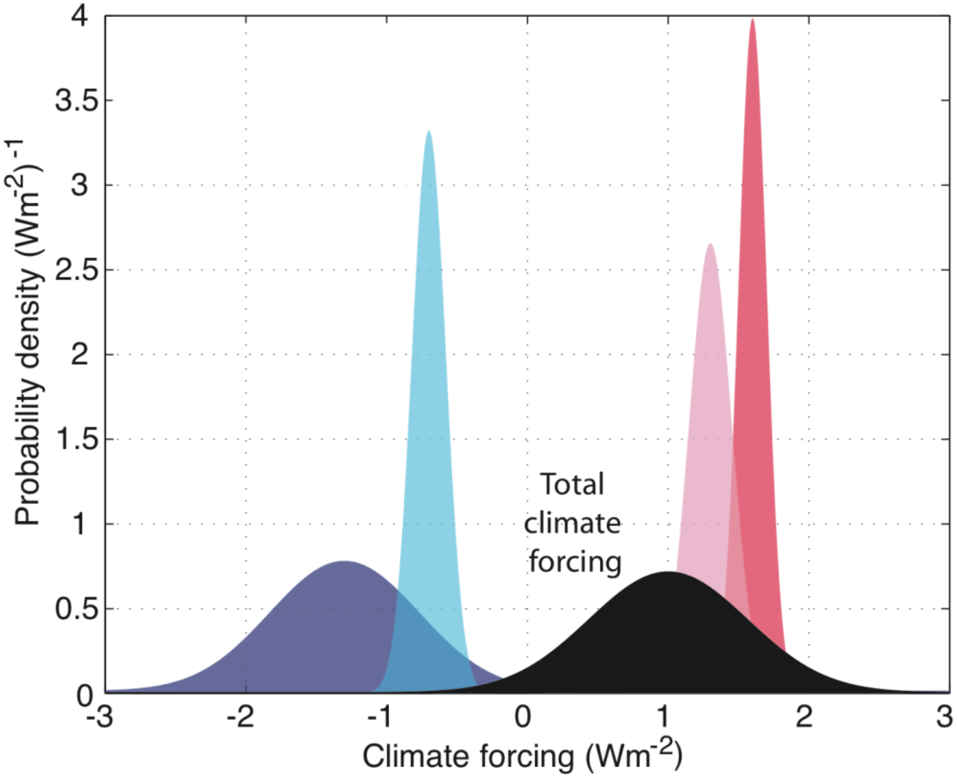
➔ Prudent not to expect big improvements any time soon….

Climate commitment

1. What if all anthropogenic emissions ceased tomorrow?

Lifetimes: CO_2: centuries to 100,000 yrs+

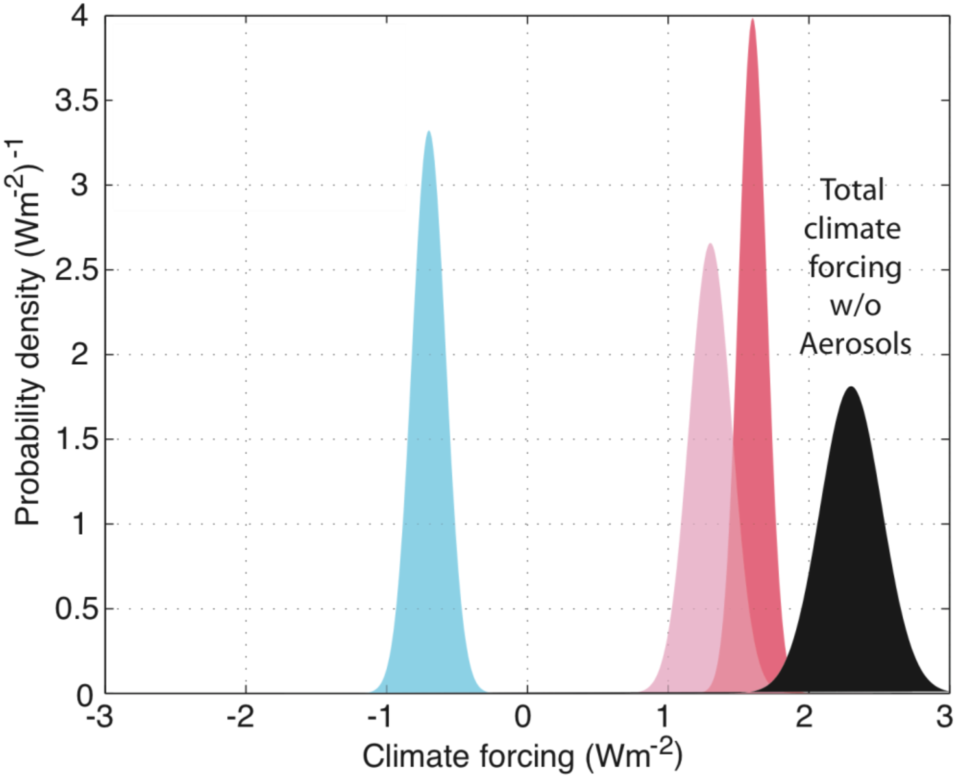
Aerosols: days to weeks



Climate commitment

1. What's already in store for us?

Lifetimes: CO_2: centuries to 100,000 yrs+
Aerosols: days to weeks

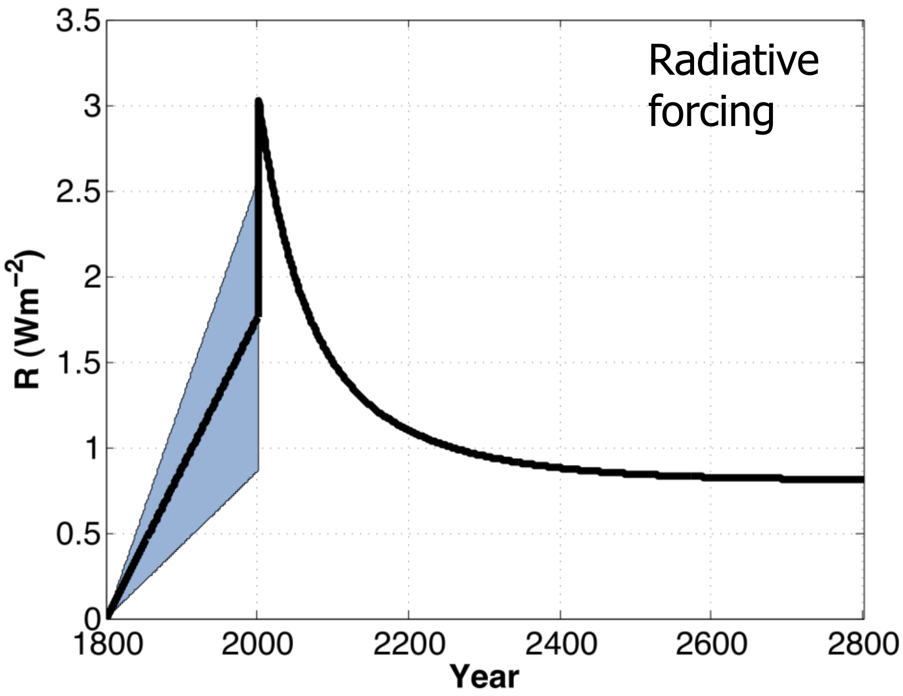


• Immediate loss of aerosols *unmasks* GHG gas warming

Climate commitment

1. What's already in store for us?

Idealized timeline of past and future climate forcing, if we stop everything today



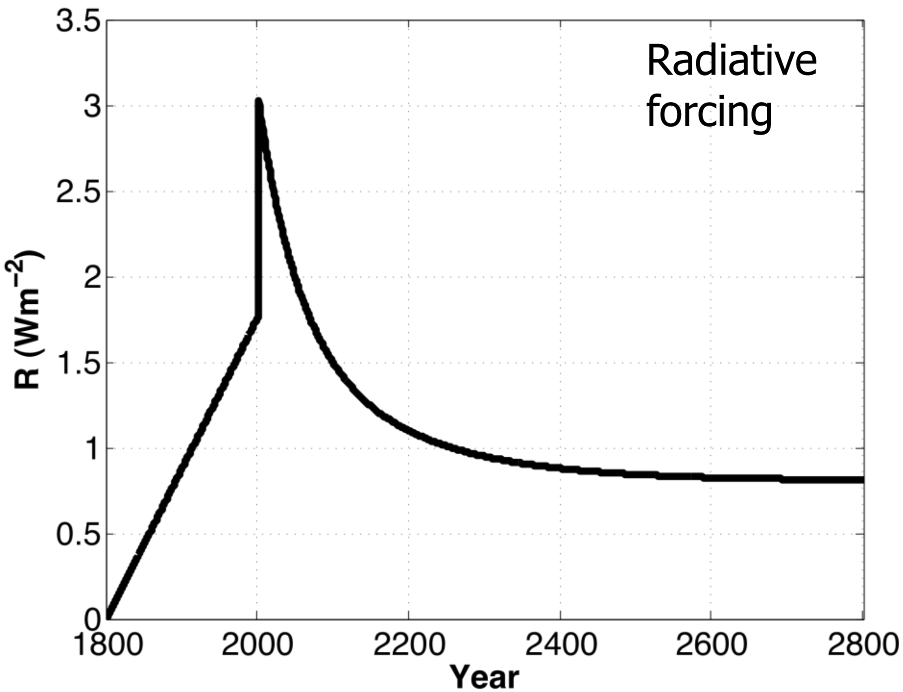
→ What does the climate do?

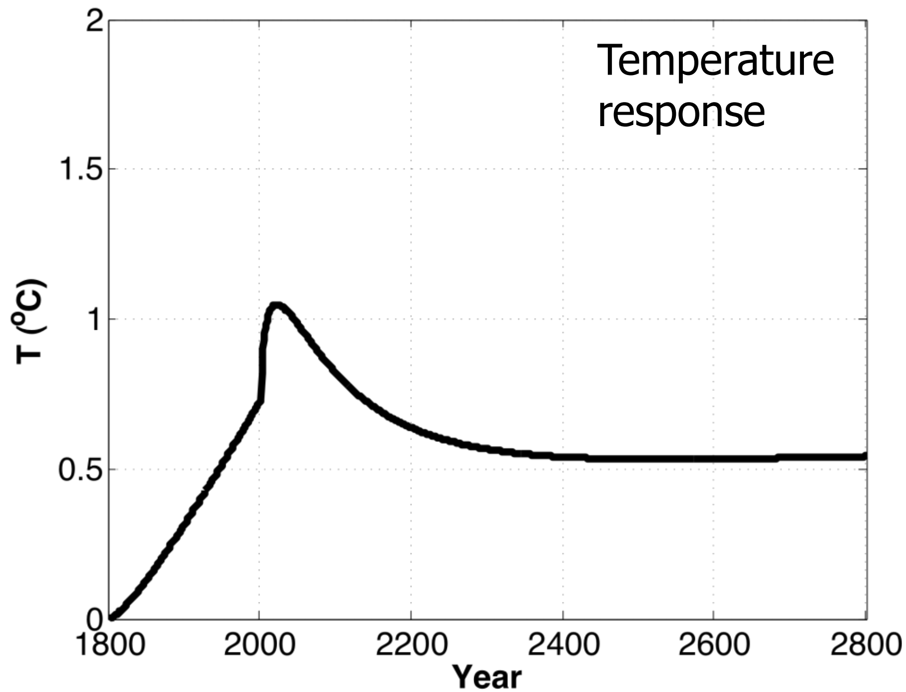
90% error bounds,
IPCC numbers,
(Kyle Armour)

Climate commitment

1. What's already in store for us?

Our best guess at what would happen



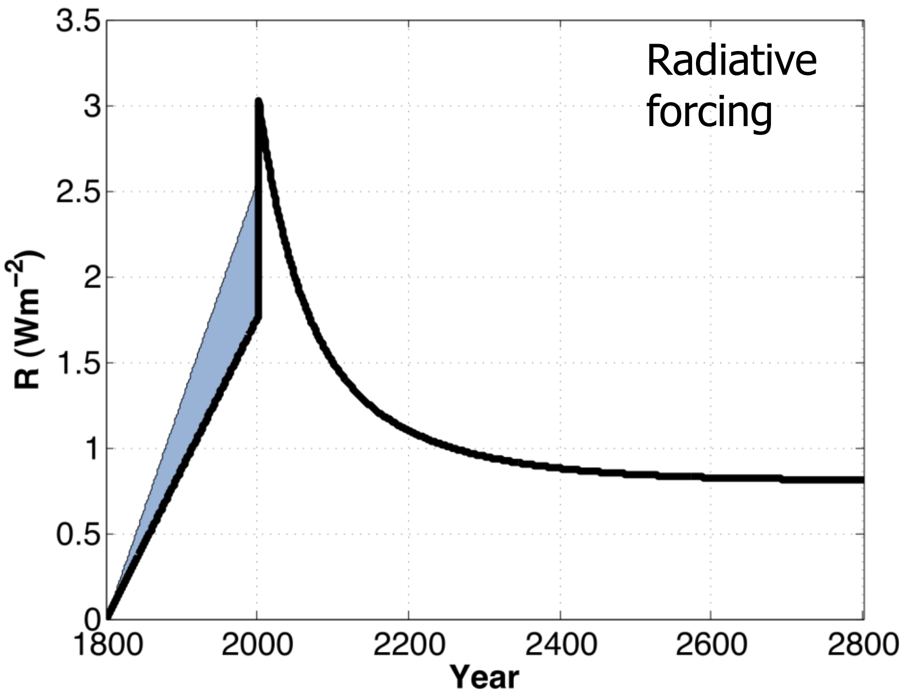


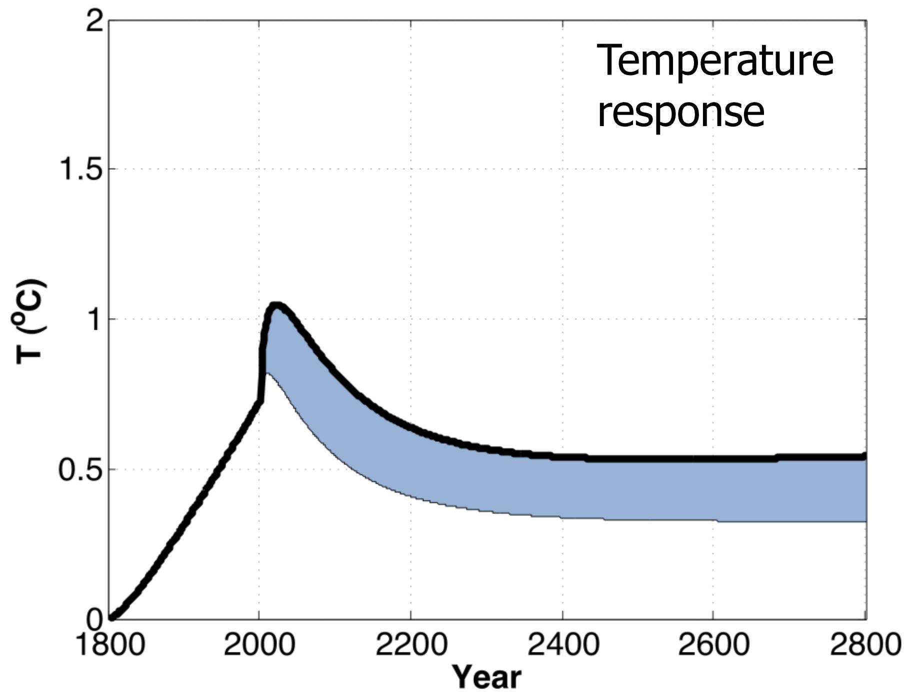
90% error bounds,
IPCC numbers,
(Kyle Armour)

Climate commitment

1. What's already in store for us?

But if past forcing has been high….



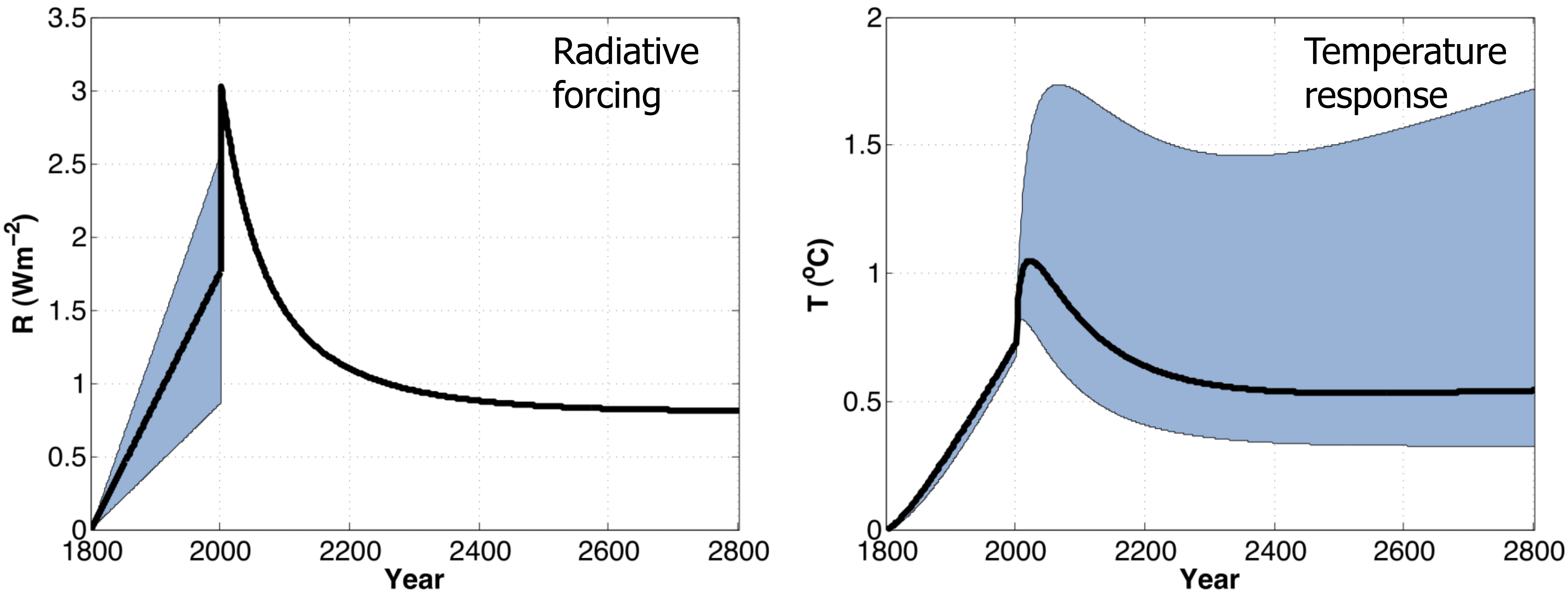


90% error bounds,
IPCC numbers,
(Kyle Armour)

Climate commitment

1. What's already in store for us?

But if past forcing has been low….



90% error bounds,
IPCC numbers,
(Kyle Armour)

Climate commitment

2. Past forcing and climate sensitivity are intrinsically related

If past forcing is strong ➔ climate sensitivity is low.

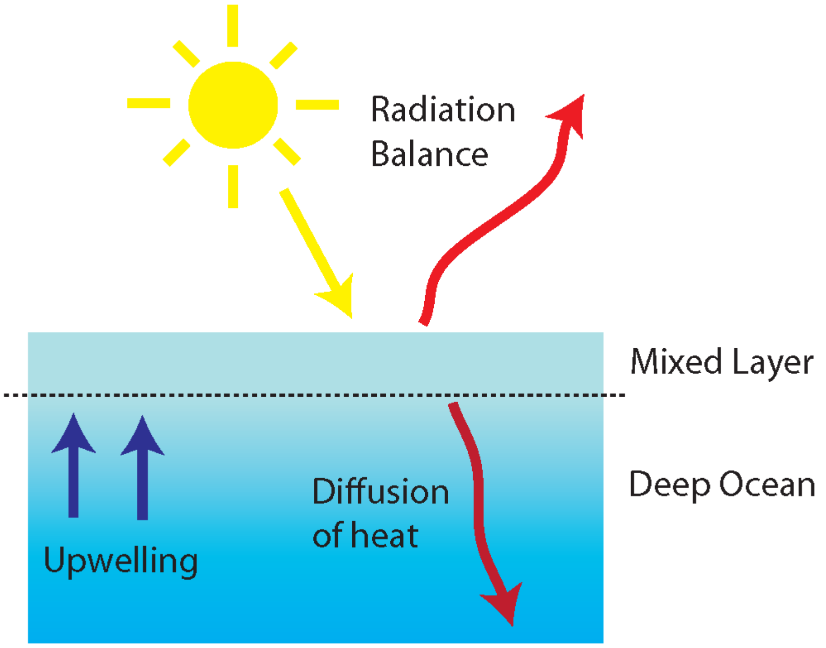
If past forcing is weak ➔ climate sensitivity is high.

For Integrated Assessment Models this matters:

– forcing (including aerosol forcing) cannot be assumed to be independent of climate sensitivity .

Transient evolution of climate

1. Heat uptake of the ocean is diffusive

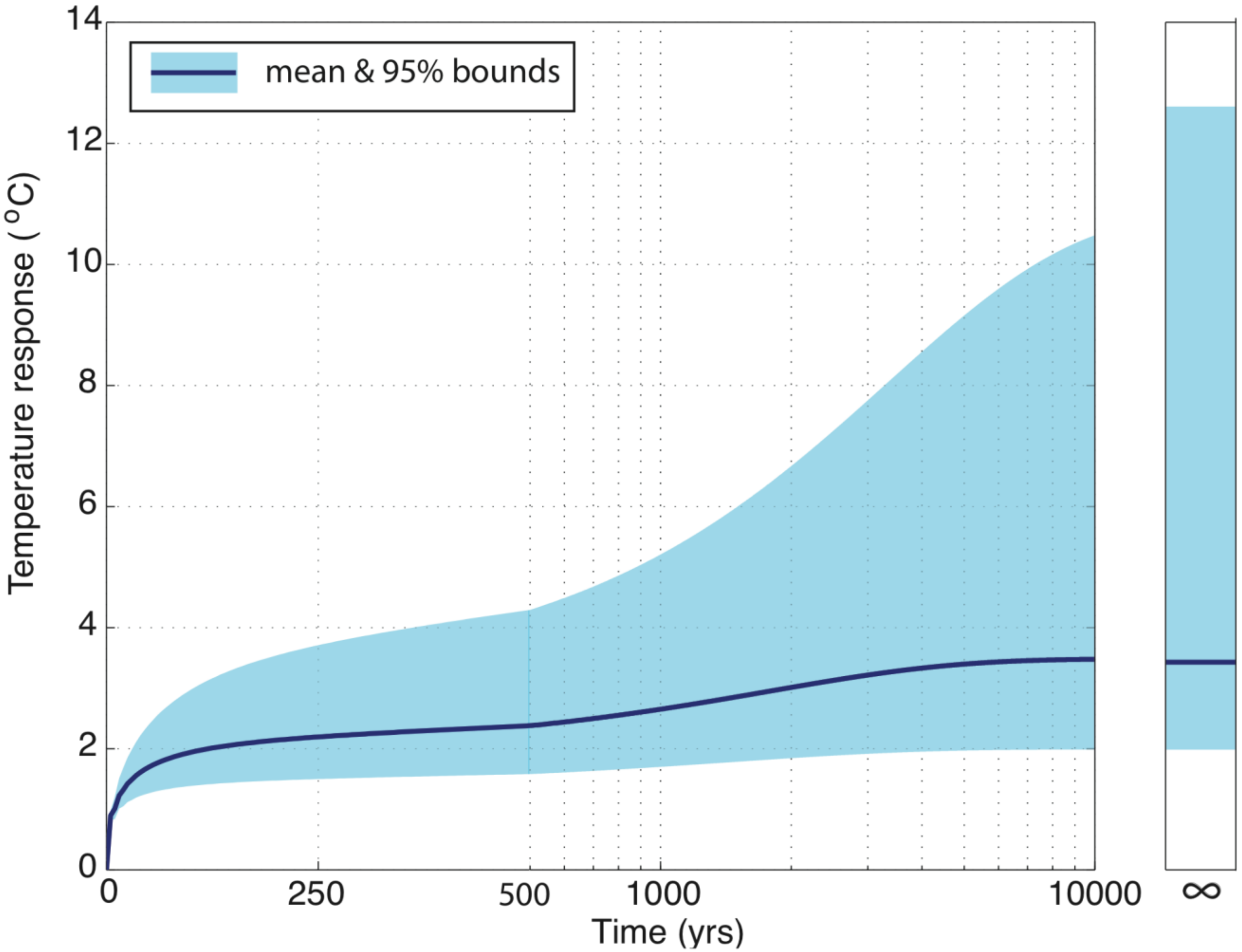


Hansen et al. (1985) show this means that

Climate adjustment time
is proportional to
(Climate Sensitivity)^2

Transient evolution of climate

2. The fat tail grows very slowly

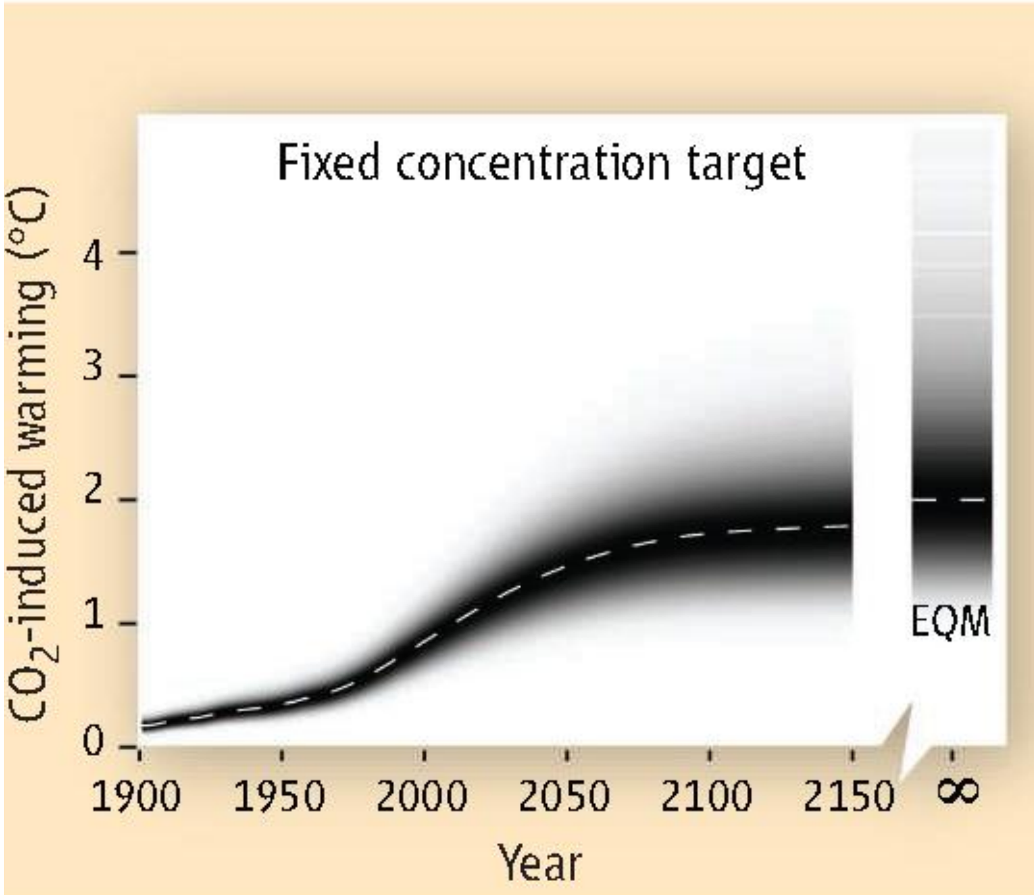


climate model response (mean & 95% bounds) to an instantaneous doubling of CO_2

- Constraining the details of the far tail of climate sensitivity is not useful on societally relevant timescales?

CO_2 stabilization targets are a mistake

1. Climate response to fixed level of CO_2 is uncertain



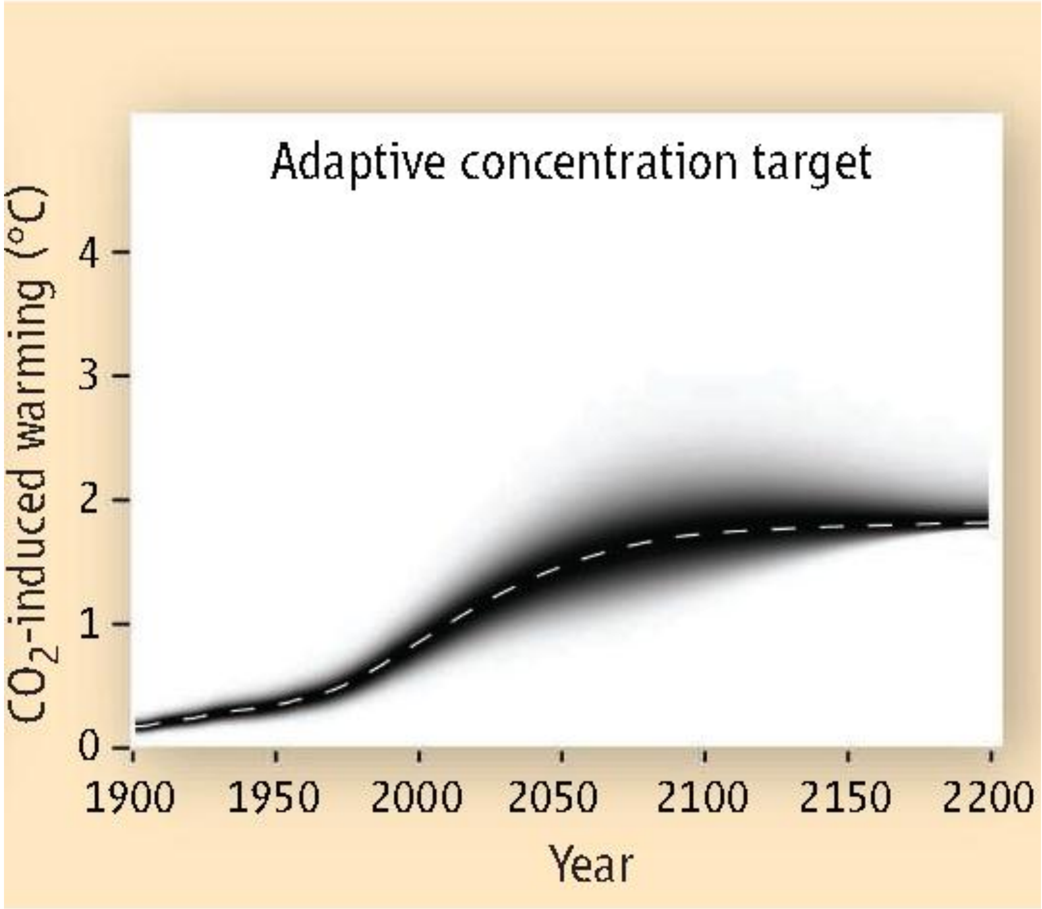
(Allen and Frame, 2007)

Stabilization target of 450 ppm at 2100

- High end sensitivities take a long, long time to be realized
- There is still considerable uncertainty at 2150.

CO_2 stabilization targets are a mistake

2. Flexibility is key



(Allen and Frame, 2007)

Concentration target adjusted at 2050.

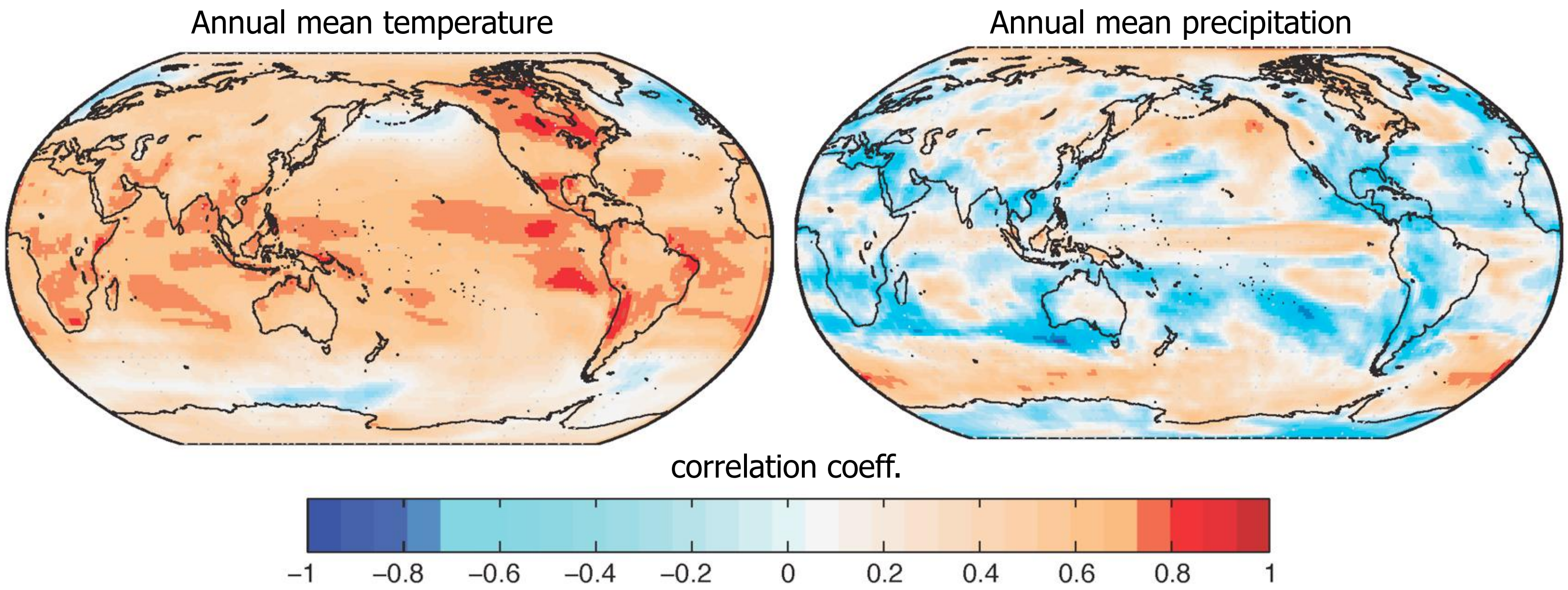
- A flexible emissions strategy is key to reaching a desired goal

Does global climate predict local climate?

1. Is climate sensitivity a good predictor of regional change?

• Among models, how well are var^{n}s in global climate sensitivity correlated with var^{n}s in regional climate change at 2100?

If |corr. coeff.| < 0.70 then <50% of local change is associated with global mean change.



• The magnitude of local changes is affected by many factors

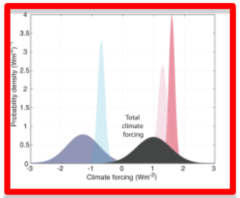
• Global ΔT is quite a poor predictor of local ΔT, ΔP

• If impacts are local, should global ΔT be used to calculate damages?

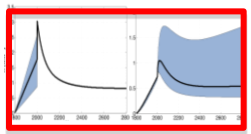
19 models from IPCC 2007 report, For more calculations see my web site. (calc^{n}s made by Nicole Feldl)

Summary:

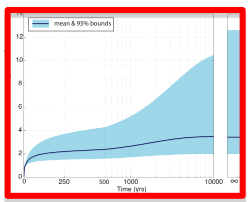
1. Uncertainty is not ignorance.
   The planet is warming and its us that's doing it.



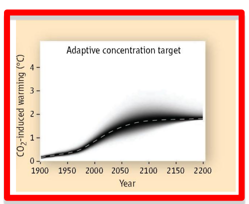
2. Climate sensitivity is uncertain b/c past forcing is uncertain (primarily aerosols).



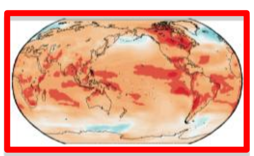
3. Uncertainty in climate sensitivity and climate forcing are not independent.



4. <u>If</u> climate sensitivity is high, it takes a very long time to get there.

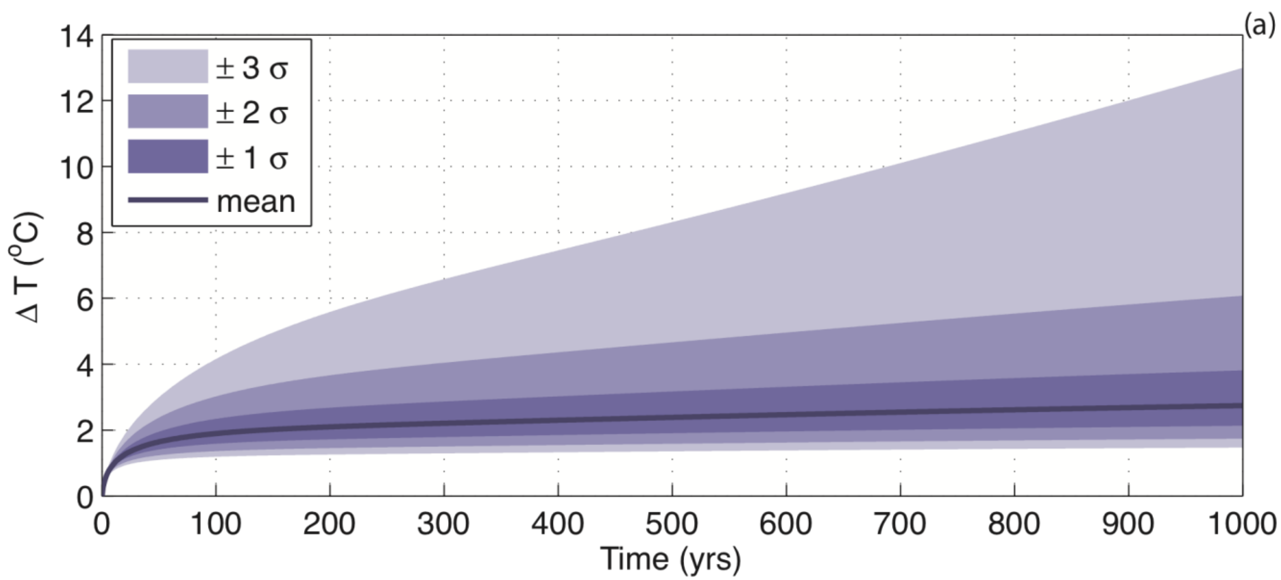


5. CO_2 stabilization targets are not an efficient way to achieve a climate goal. (flexibility is vital)



6. Global climate is not a strong predictor of local climate change.

Extra slides….


(a)
± 3 σ
± 2 σ
± 1 σ
mean
Δ T (°C)
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900
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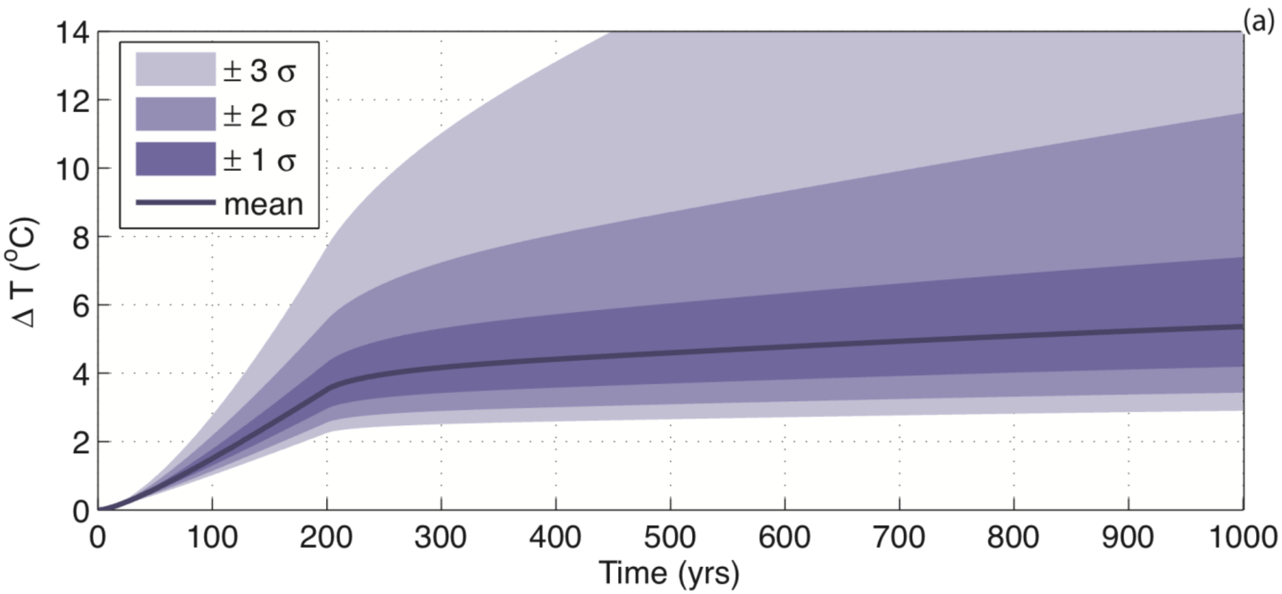
Time (yrs)



(a)
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Time (yrs)
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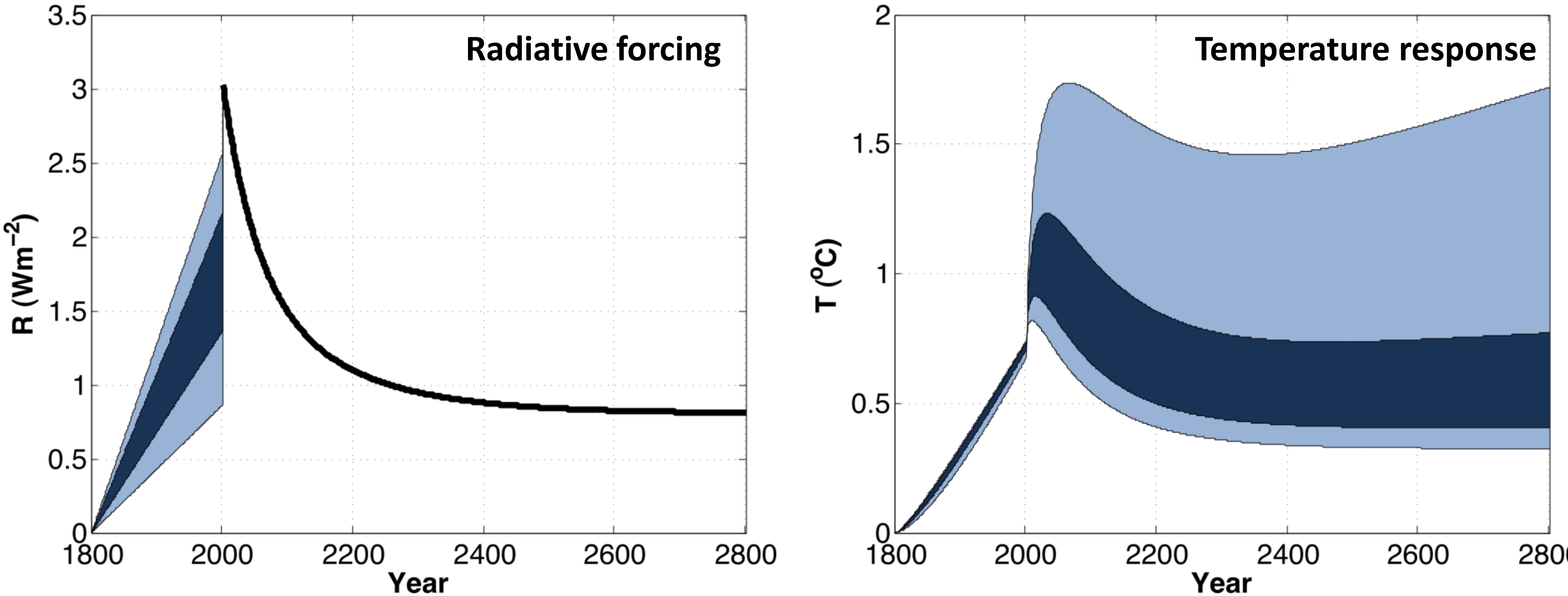
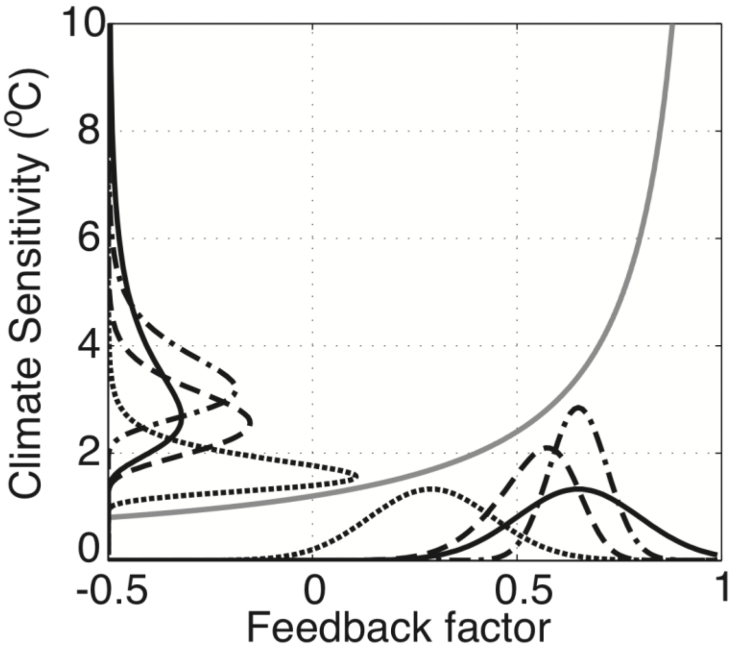
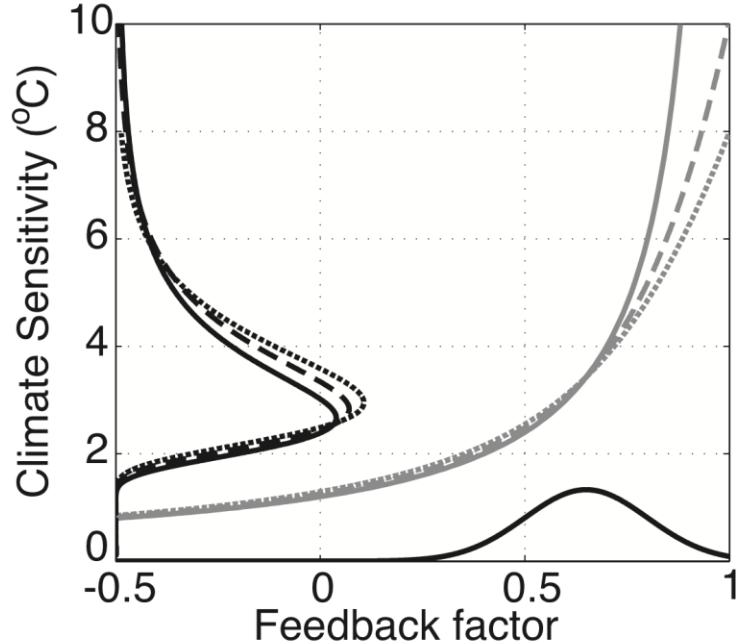
AR4 models undersample climate commitment



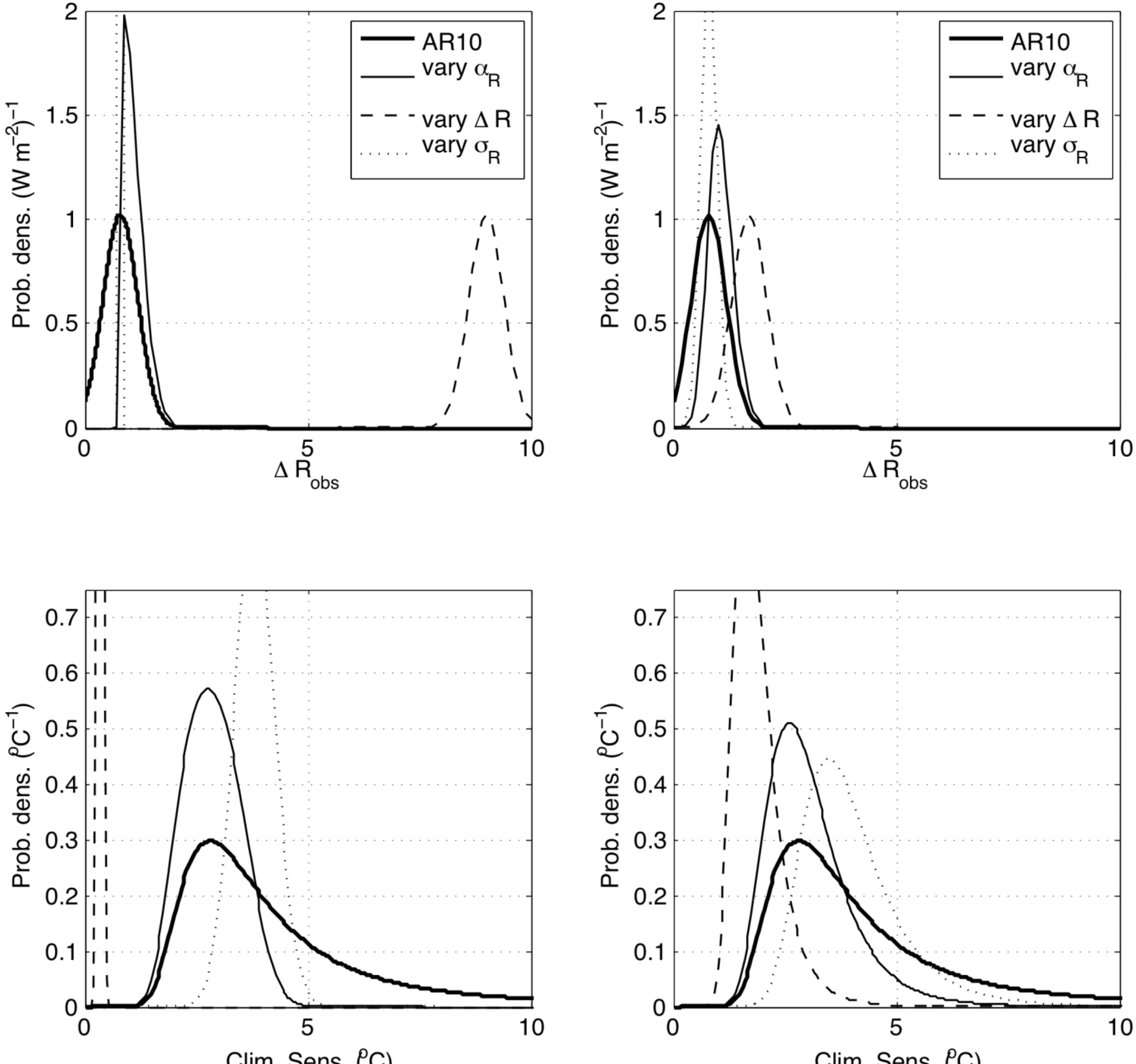
- Dark blue is the IPCC 'likely' (68% confidence interval) range of climate sensitivity (2 to 4.5 C) and implied range of radiative forcing
- AR4 climate models span only this 'likely' range
- R and λ are correlated within AR4 and older models (Kiehl 2007, Knutti 2008)

Effects of nonlinearity of climate feedbacks



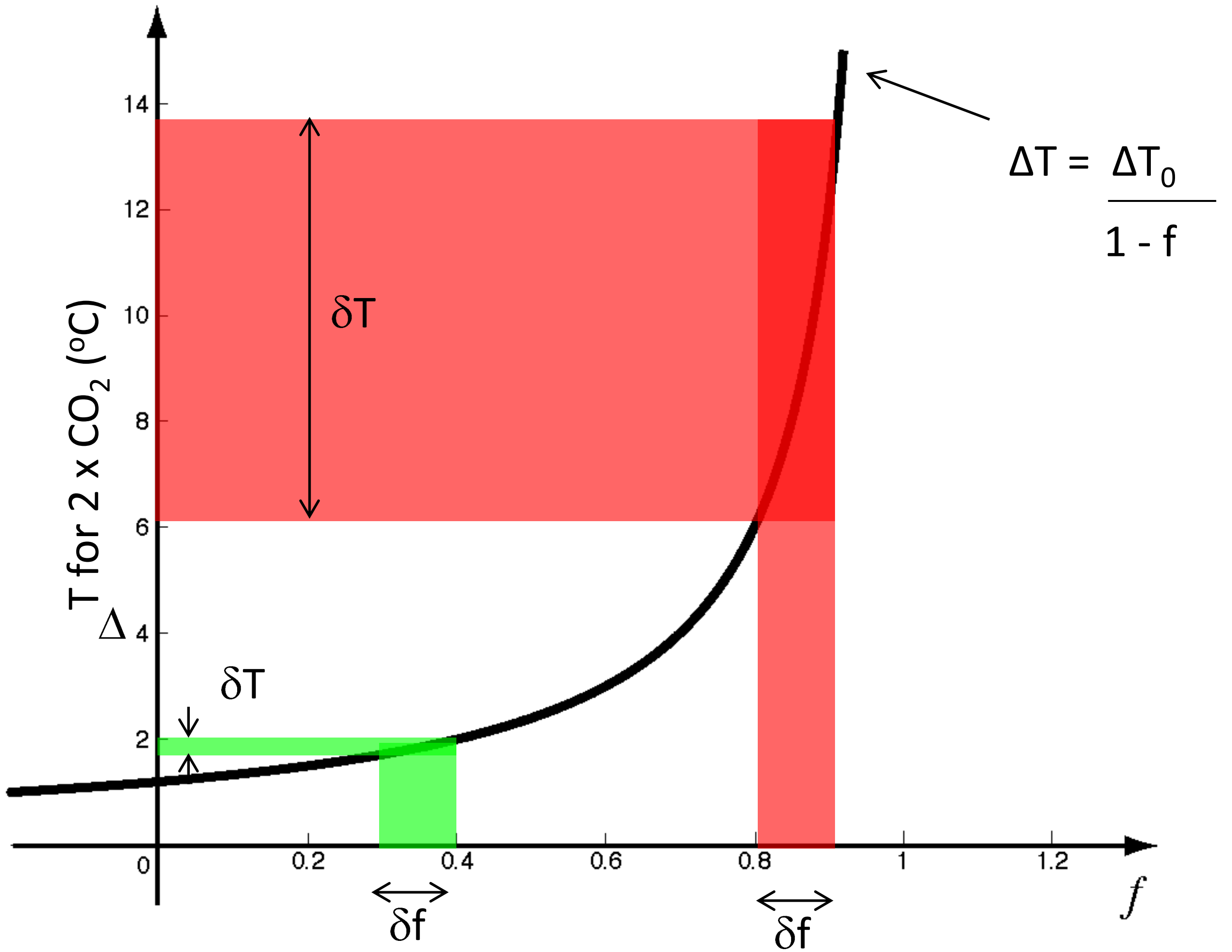


By how much do observations have to change to change climate sensitivity



Aspects of feedbacks III.

How does uncertainty in feedbacks translate into uncertainty in the system response?



Systems of strong positive feedbacks inherently less predictable

Martin L. Weitzman
Notes for EPA & DOE discussion meeting
November, 2010

A. First thoughts on "'thinking about' high-temperature damages from potential catastrophes in climate change."

'Thinking about' is the right phrase. This is a notoriously intractable area even to conceptualize, much less to model or to quantify. Don't expect miracles or breakthroughs here — too many "unknown unknowns" with seemingly non-negligible probabilities to feel comfortable with.

B. What is the nature of the beast?

The economics of climate change consists of a very long chain of tenuous inferences fraught with big uncertainties in every link: beginning with unknown base-case GHG emissions; then compounded by big uncertainties about how available policies and policy levers will transfer into actual GHG emissions; compounded by big uncertainties about how GHG flow emissions accumulate via the carbon cycle into GHG stock concentrations; compounded by big uncertainties about how and when GHG stock concentrations translate into global average temperature changes; compounded by big uncertainties about how global average temperature changes decompose into regional climate changes; compounded by big uncertainties about how adaptations to, and mitigations of, regional climate-change damages are translated into regional utility changes via a regional "damages function"; compounded by big uncertainties about how future regional utility changes are aggregated into a worldwide utility function and what should be its overall degree of risk aversion; compounded by big uncertainties about what discount rate should be used to convert everything into expected-present-discounted values. The result of this lengthy cascading of big uncertainties is a reduced form of truly enormous uncertainty about an integrated assessment problem whose structure wants badly be transparently understood and stress tested for catastrophic outcomes.

Let welfare W stand for expected present discounted utility, whose theoretical upper bound is B. Let $D \equiv B-W$ be expected present discounted disutility. Here D stands for what might be called the "diswelfare" of climate change. Unless otherwise noted, my default meaning of the term "fat tail" (or "thin tail") will concern the upper tail of the PDF of $\ln D$, resulting from whatever combination of probabilistic temperature changes, temperature-sensitive damages, discounting, and so forth, by which this comes about. Empirically, it is not the fatness of the tail of temperature PDFs *alone* or the reactivity of the damages function to high temperatures *alone*, or any other factor *alone*, that counts, but the *combination* of all such factors. Probability of welfare-loss catastrophe declines in impact size, but key question here is: *how fast* a decline relative to size of catastrophe? When we turn to theory, it seems to highlight that the core "tail fattening" mechanism is an inherent inability to learn about extreme events from limited data.

C. What do rough calculations show about this beast?

I have played with some extremely rough numerical examples. GHG concentration implies a PDF of temperature responses implies a PDF of damages (given a "damages function"). In order to get tail fatness to matter for willingness to pay to avoid climate change requires a *much* more reactive damages function than the usual quadratic. Usual quadratic damages function loses 26% of output for a 12dC temperature change. At 2% annual growth rate, 12dC change 200 years from now implies that welfare-equivalent consumption then will still be *37 times higher than today*. If you use the standard quadratic damages function, you cannot get much damage from extreme temperatures. If make a reactive damages function, such that, say, 12dC temperature increase causes welfare-equivalent consumption to shrink to, say, 5% of today's level, then get very high WTP to reduce GHG target levels. Model is terrified of flirting with high CO2-e levels, especially above 700 ppm. Incredible dependence on degree of risk aversion (2, 3, or 4?), fatness of tail PDFs (climate sensitivity PDF: normal, lognormal, Pareto?), and so forth. My own tentative summary conclusion: tail of extreme climate change welfare-loss possibilities is much too fat for comfort when combined with reactive damages at high temperatures. It looks like this could influence such things as social cost of carbon.

D. Is there anything constructive to take away from this gloomy beast?

My tentative answer: a qualified maybe. Some possible rough ideas follow.

1. Keep a sense of balance. A small but fat-tailed probability of disastrous damages is not a realization of a disaster. Highly likely outcome is a future sense that we dodged a bullet (like Cuban missile crisis?). Yet when all is said and done, catastrophic climate change looks to me like a very serious issue.

2. Try standard CBA or IAM exercises in good faith. *But*, be prepared – when dealing with extremes – that answers might depend non-robustly upon seemingly-obscure assumptions about tail fatness, about how the extreme damages are specified (functional forms, parameter values, etc.), assumptions about rates of pure time preference, degrees of risk aversion, Bayesian learning, CO2 stock inertia, CH4 releases from clathrates, mid-course correction possibilities, etc. Some crude calculations seem to indicate great welfare sensitivity to seemingly-obscure factors such as the above, most of which are difficult to know with any degree of precision. Do CBAs and IAMs, study answers, but maybe don't try to deny the undeniable if these answers are sensitive to tail assumptions in a highly nonlinear welfare response to extreme uncertainty.

3. Should we admit to the public that climate change CBA looks more iffy and less robust than, say, CBA of SO2 abatement, or would this be self defeating?

4. Maybe there should be relatively more research emphasis on understanding extreme tail behavior of climate-change welfare disasters. Alas, this is very easy to say but very difficult to enact. How do we learn the fatness of PDF tails from limited observations or experience?

5. A need to compare how fat are tails of climate-change welfare loss with how fat are tails of any proposed solutions, such as nuclear power, below-ground carbon sequestration, etc.

6. Suppose that a lot of expected present discounted disutility is in the bad fat tail of the welfare-loss PDF. Realistically, how can we limit some of the most horrific losses in worst-case scenarios? Can we filter-learn fast enough to offset residence time of atmospheric CO2 stocks by altering GHG emission flows in time to work? Is tail fatness an argument for developing an emergency-standby backstop role for fast geoengineering? Any other backstop options? Take-home lesson here: hope for the best and prepare for the worst. At least we should be prepared, beforehand, for dealing with ugly scenarios, even if they are low-probability events. Should the discussion about emergency preparedness begin now?

Earth System Tipping Points

Timothy M. Lenton
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Definitions

A **tipping point** is a critical threshold at which the future state of a system can be qualitatively altered by a small change in forcing[1]. A **tipping element** is a part of the Earth system (at least sub-continental in scale) that has a tipping point[1]. Policy-relevant tipping elements are those that could be forced past a tipping point this century by human activities. **Abrupt climate change** is the subset of tipping point change which occurs faster than its cause[2]. Tipping point change also includes transitions that are slower than their cause (in both cases the rate is determined by the system itself). In either case the change in state may be reversible or irreversible. **Reversible** means that when the forcing is returned below the tipping point the system recovers its original state (either abruptly or gradually). **Irreversible** means that it does not (it takes a larger change in forcing to recover). Reversibility in principle does not mean that changes will be reversible in practice.

Tipping elements in the Earth's climate system

Previous work[1] identified a shortlist of nine potential policy-relevant tipping elements in the climate system that could pass a tipping point this century and undergo a transition this millennium under projected climate change. These are shown with some other candidates in Figure 1.

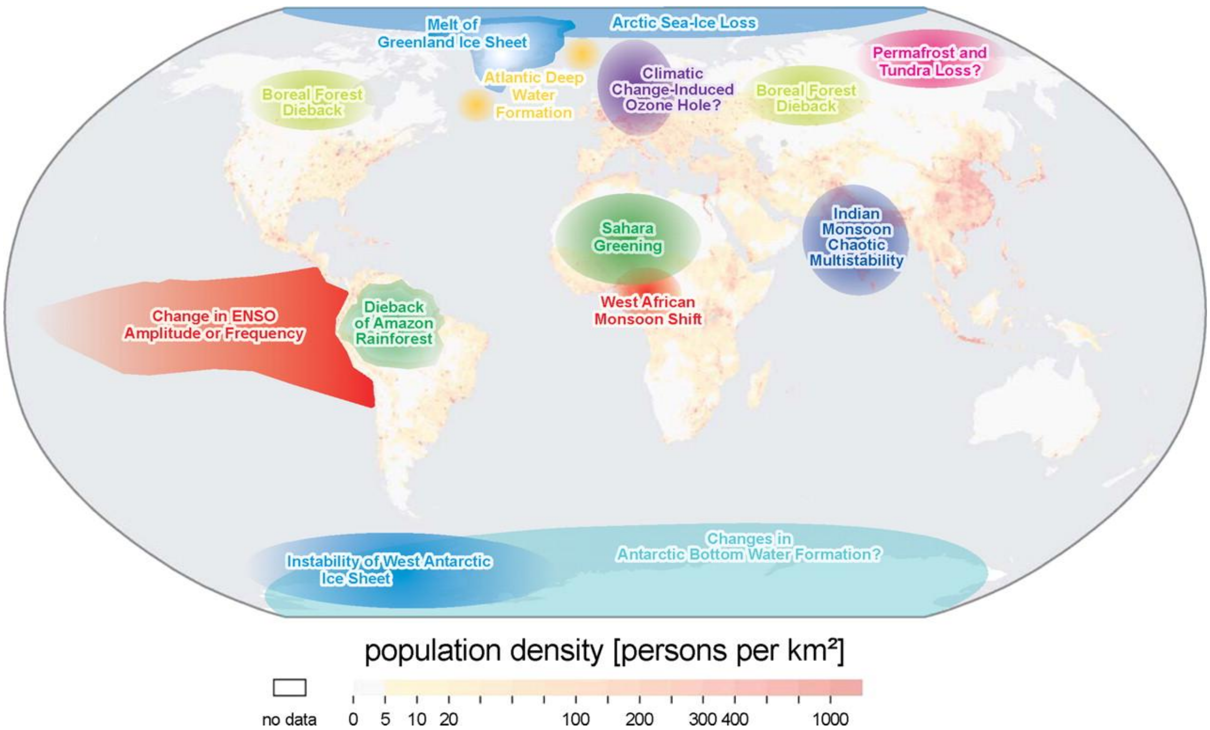

Figure 1: Map of potential policy-relevant tipping elements in the Earth's climate system overlain on population density. Question marks indicate systems whose status as tipping elements is particularly uncertain.

We should be most concerned about those tipping points that are nearest (least avoidable) and those that have the largest negative impacts. Generally, the more rapid and less reversible a transition is, the greater its impacts. Additionally, any positive feedback to global climate change may increase concern, as can interactions whereby tipping one element encourages tipping another. The proximity of some tipping points has been assessed through expert elicitation[1,3]. Proximity, rate and reversibility have been also assessed through literature review[1], but there is a need for more detailed consideration of impacts[4]. The following are some of the most concerning tipping elements:

The **Greenland ice sheet** (GIS) may be nearing a tipping point where it is committed to shrink[1,3]. Striking amplification of seasonal melt was observed in summer 2007 associated with record Arctic sea-ice loss[5]. Once underway the transition to a smaller ice cap will have low reversibility, although it is likely to take several centuries (and is therefore not abrupt). The impacts via sea level rise will ultimately be large and global, but will depend on the rate of ice sheet shrinkage. Latest work suggests there may be several stable states for ice volume, with the first transition involving retreat of the ice sheet onto land and around 1.5 m of sea level rise[6].

The **West Antarctic ice sheet** (WAIS) is currently assessed to be further from a tipping point than the GIS, but this is more uncertain[1,3]. Recent work has shown that multiple stable states can exist for the grounding line of the WAIS, and that it has collapsed repeatedly in the past. It has the potential for more rapid change and hence greater impacts than the GIS.

The **Amazon rainforest** experienced widespread drought in 2005 turning the region from a sink to a source (0.6-0.8 PgC yr^{-1}) of carbon[7]. If anthropogenic-forced[8] lengthening of the dry season continues, and droughts increase in frequency or severity[9], the rainforest could reach a tipping point resulting in dieback of up to ~80% of the rainforest[10-13], and its replacement by savannah. This could take a few decades, would have low reversibility, large regional impacts, and knock-on effects far away. Widespread dieback is expected in a >4 °C warmer world[3], and it could be committed to at a lower global temperature, long before it begins to be observed[14].

The **Sahel and West African Monsoon** (WAM) have experienced rapid but reversible changes in the past, including devastating drought from the late 1960s through the 1980s. Forecast future weakening of the Atlantic thermohaline circulation contributing to 'Atlantic Niño' conditions, including strong warming in the Gulf of Guinea[15], could disrupt the seasonal onset of the WAM[16] and its later 'jump' northwards[17] into the Sahel. Whilst this might be expected to dry the Sahel, current global models give conflicting results. In one, if the WAM circulation collapses, this leads to wetting of parts of the Sahel as moist air is drawn in from the Atlantic to the West[15,18], greening the region in what would be a rare example of a positive tipping point.

The **Indian Summer Monsoon** (ISM) is probably already being disrupted[19,20] by an atmospheric brown cloud (ABC) haze that sits over the sub-continent and, to a lesser degree, the Indian Ocean. The ABC haze is comprised of a mixture of soot, which absorbs sunlight, and some reflecting sulfate. It causes heating of the atmosphere rather than the land surface, weakening the seasonal establishment of a land-ocean temperature gradient which is critical in triggering monsoon onset[19]. Conversely, greenhouse gas forcing is acting to strengthen the monsoon as it warms the northern land masses faster than the ocean to the south. In some future projections, ABC forcing could double the drought frequency within a decade[19] with large impacts, although it should be highly reversible.

Estimation of likelihood under different scenarios

If we pass climate tipping points due to human activities (which in IPCC language are called "large scale discontinuities"[21]), then this would qualify as dangerous anthropogenic interference (DAI) in the climate system. Relating actual regional tipping points to e.g. global mean temperature change is always indirect, often difficult and sometimes not meaningful. Recent efforts suggest that 1 °C global warming (above 1980-1999) could be dangerous as there are "moderately significant"[21] risks of large scale discontinuities, and Arctic sea-ice and possibly the Greenland ice sheet would be threatened[1,22]. 3 °C is clearly dangerous as risks of large scale discontinuities are "substantial or severe"[21], and several tipping elements could be threatened[1]. Under a 2-4 °C committed warming, expert elicitation[3] gives a >16% probability of crossing at least 1 of 5 tipping points, which rises to >56% for a >4 °C committed warming. Considering a longer list of 9 potential tipping elements, Figure 2 summarizes recent information on the likelihood of tipping them under the IPCC range of projected global warming this century.

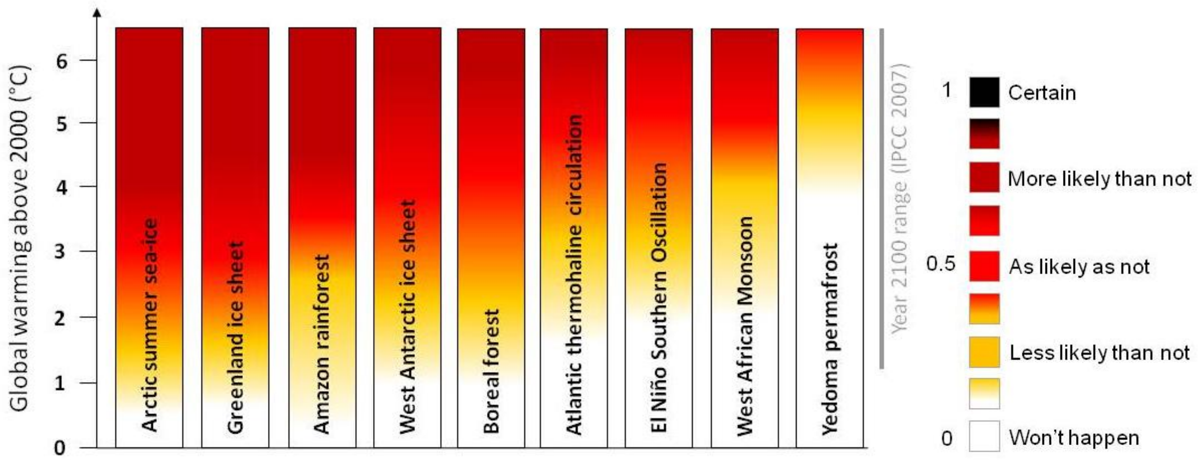

Figure 2: Burning embers diagram for the likelihood of tipping different elements under different degrees of global warming[23] – updated, based on expert elicitation results[3] and recent literature.

Early warning prospects

An alternative approach to assessing the likelihood of tipping different elements is to try and directly extract some information on their present stability (or otherwise). Recent progress has been made in identifying and testing generic potential early warning indicators of an approaching tipping point[1,24-27]. Slowing down in response to perturbation is a nearly universal property of systems approaching various types of tipping point[25,27]. This has been successfully detected in past climate records approaching different transitions[24,25], and in model experiments[24-26]. Other early warning indicators that have been explored for ecological tipping points[28], include increasing variance[28], skewed responses[28,29] and their spatial equivalents[30]. These are beginning to be applied to anticipating climate tipping points. For climate sub-systems subject to a high degree of short timescale variability ('noise'), flickering between states may occur prior to a more permanent transition[31]. For such cases, we have recently developed a method of deducing the number of states (or 'modes') being sampled by a system, their relative stability (or otherwise), and changes in these properties over time[32].

Applying these methods to observational and reconstructed climate indices leading up to the present, we find that the Atlantic Multi-decadal Oscillation (AMO) index, which is believed to reflect fluctuations in the underlying strength of the thermohaline circulation, is showing signs of slowing down (i.e. decreasing stability) and of the appearance of a second state (or mode of behavior). On interrogating the underlying sea surface temperature data (used to construct the index), we find that recent significant changes are localized in the northernmost North Atlantic, and are investigating the possible relationship with changes in Arctic sea-ice cover. Meanwhile, some other climate indices, e.g. the Pacific Decadal Oscillation (PDO) show signs of increasing stability.

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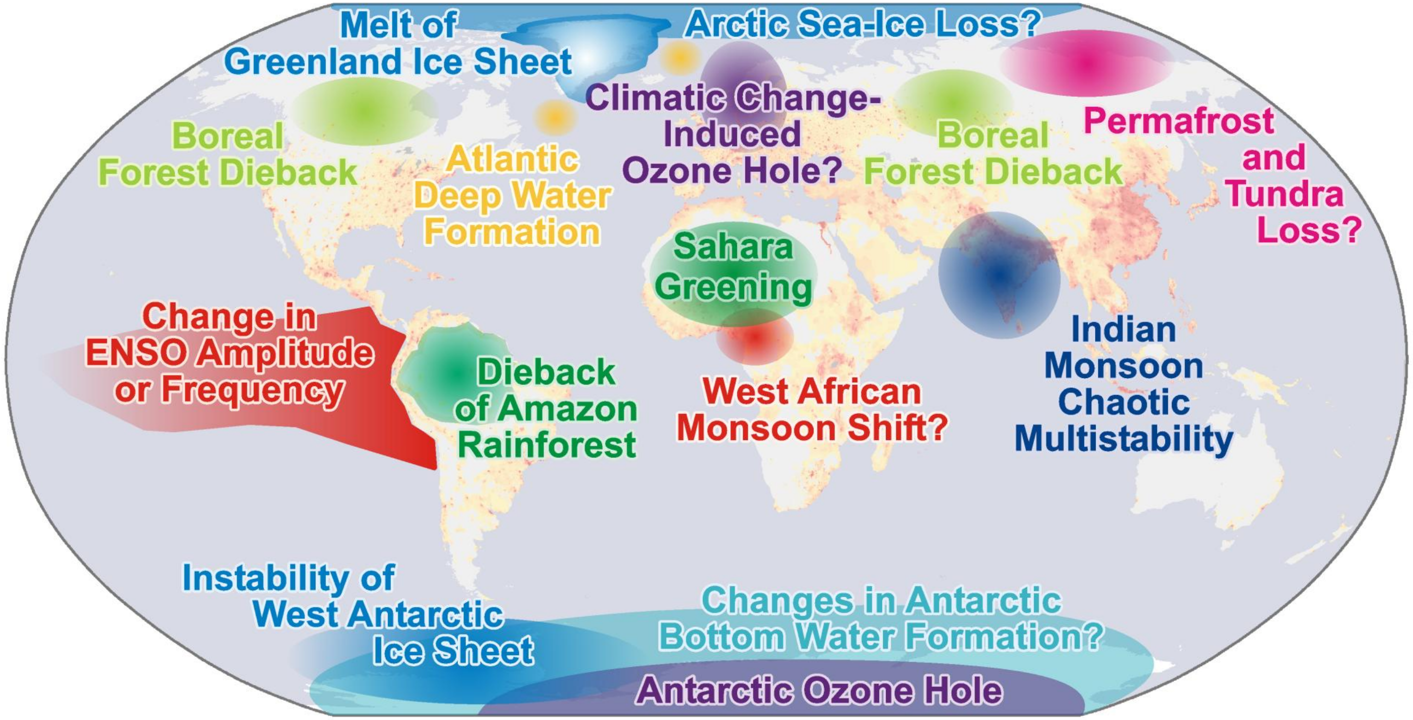
Earth system tipping points



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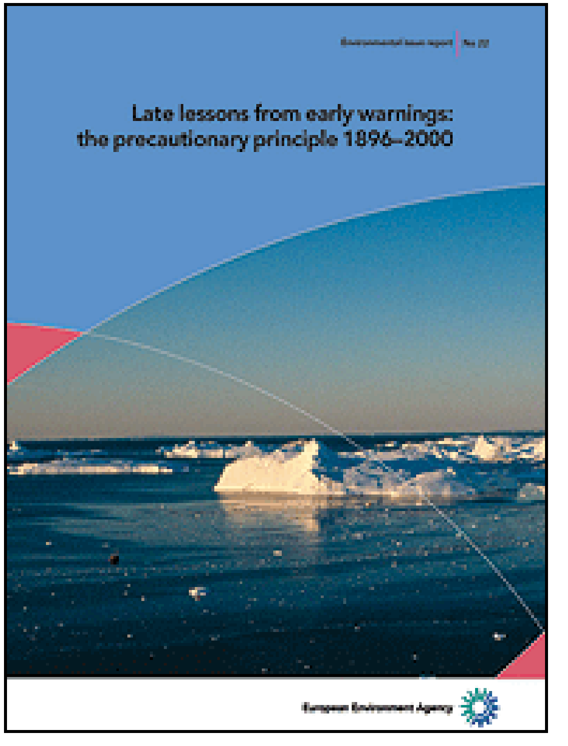
Outline

University of East Anglia

- Evidence on tipping points
- Probability under different scenarios
- Early warning prospects



“Little things can make a big difference”

Lenton et al. (2008) *PNAS* 105(6): 1786-1793

Tipping element

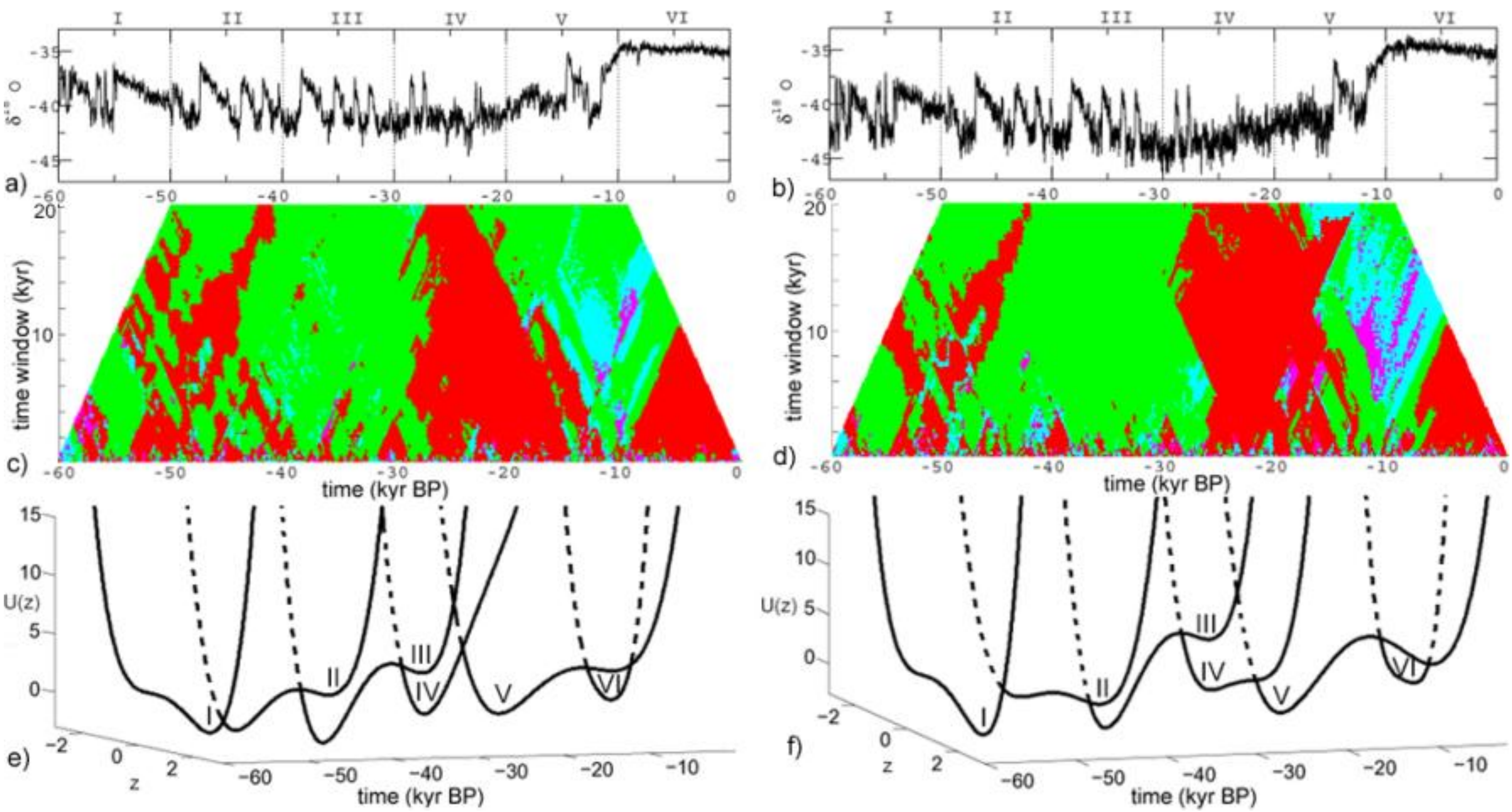
- A component of the Earth system, at least sub-continental in scale (~1000km), that can be switched – under certain circumstances – into a qualitatively different state by a small perturbation.

Tipping point

- The corresponding critical point – in forcing and a feature of the system – at which the future state of the system is qualitatively altered.

Changing climate states in the past

Livina, Kwasniok & Lenton (2010) *Climate of the Past,* 6: 77-82



Number of states: 1, 2, 3, 4

Policy relevant tipping elements

Lenton et al. (2008) *PNAS* 105(6): 1786-1793

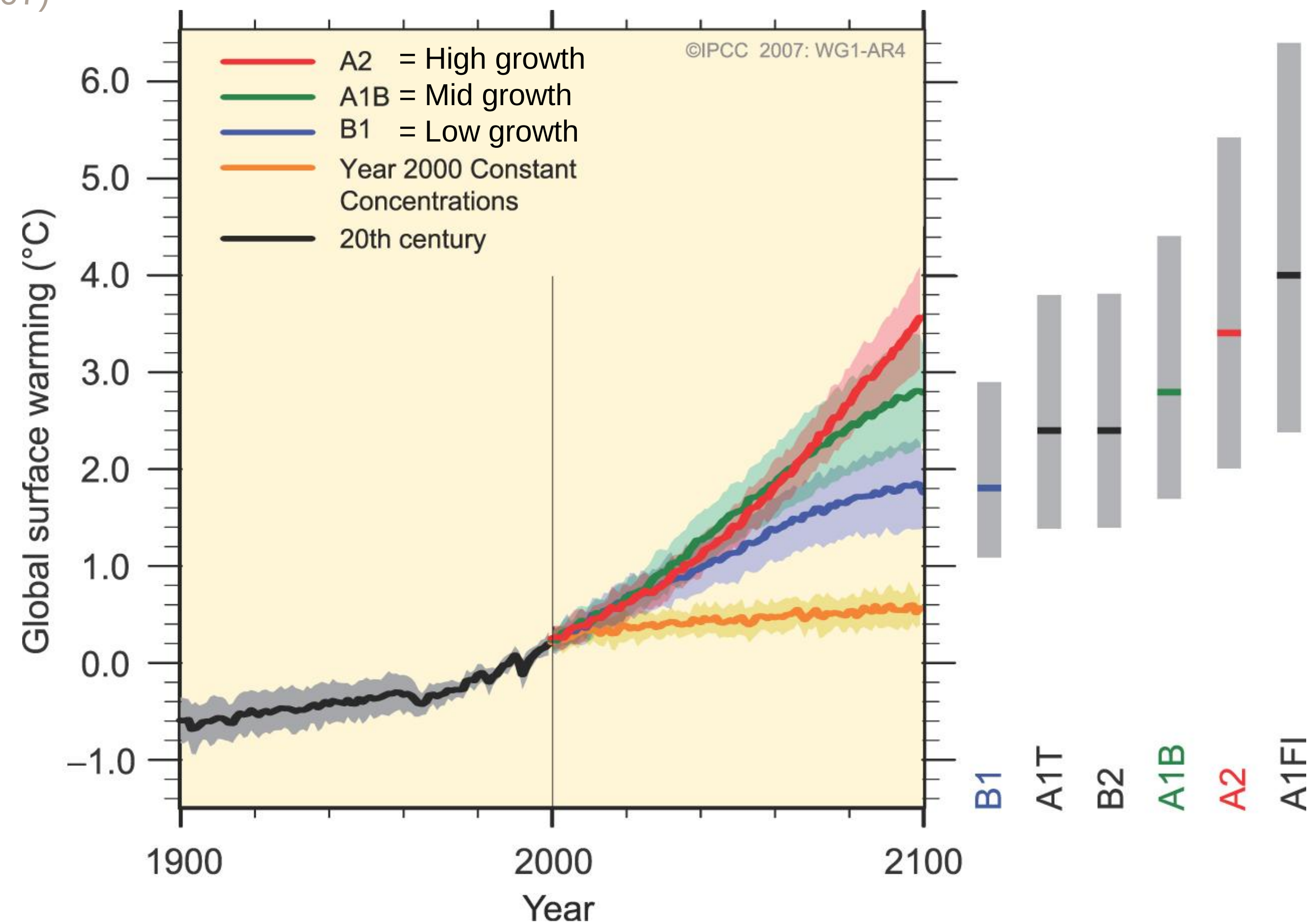
- Human activities are interfering with the system such that decisions taken within a “political time horizon” (~100 years) can determine whether the tipping point is reached.

- The time to observe a qualitative change plus the time to trigger it lie within an “ethical time horizon” (~1000 years).

- A significant number of people care about the fate of the system.

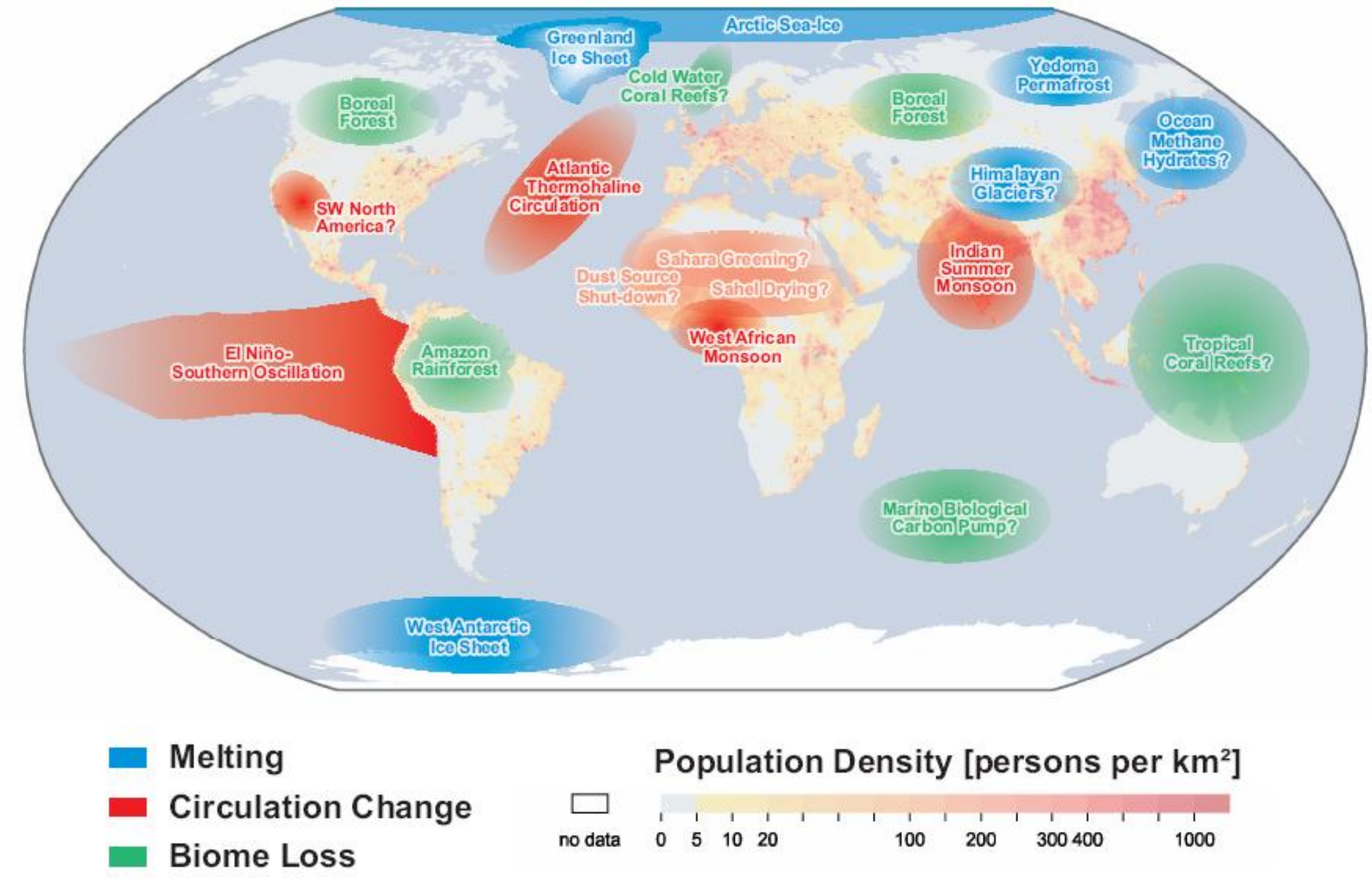
Policy-relevant forcing range

IPCC (2007)



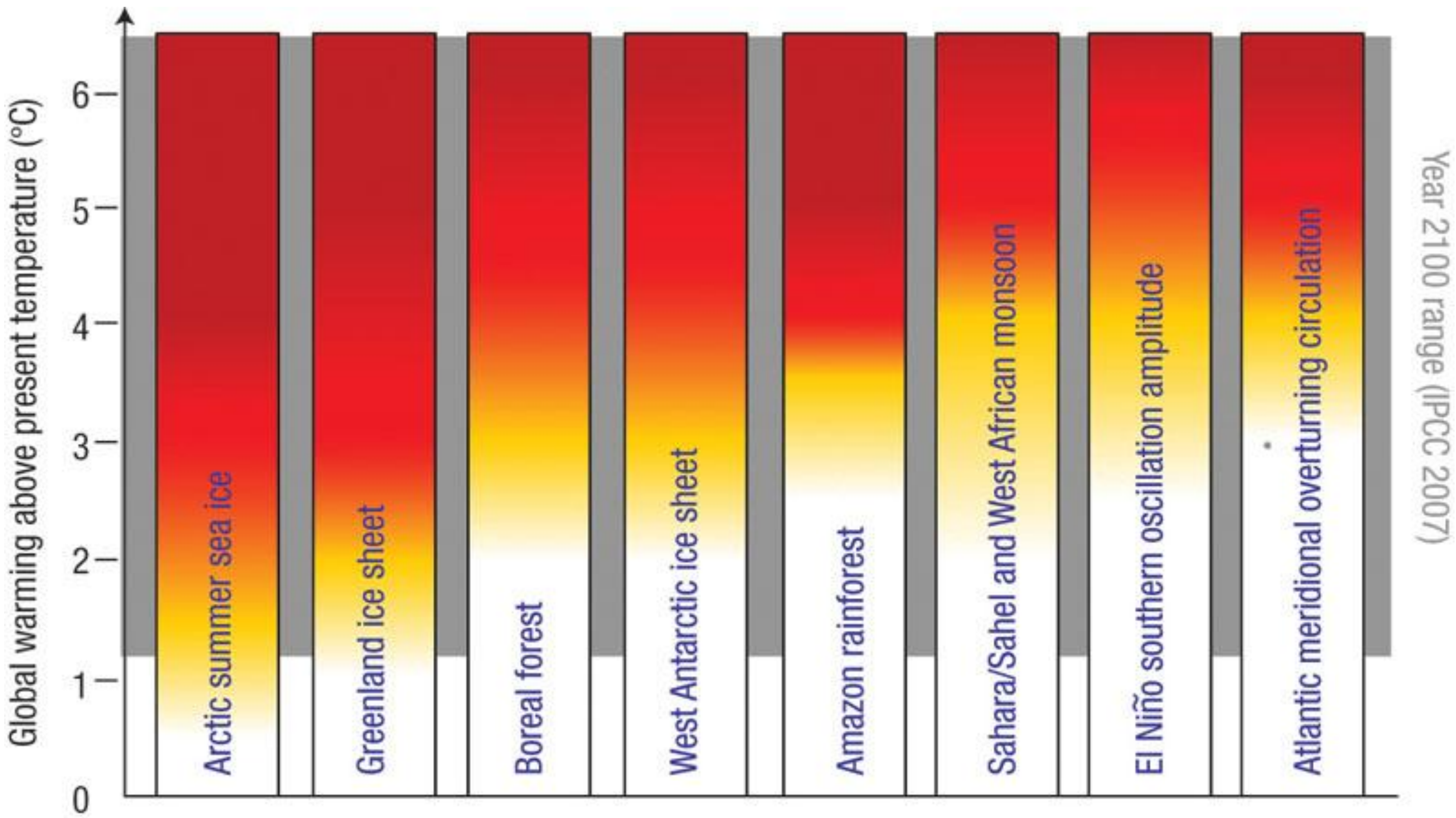
Tipping elements in the Earth system

Revised after Lenton *et al.* (2008) *PNAS* 105(6): 1786-1793



Estimates of proximity

Lenton & Schellnhuber (2007) *Nature Reports Climate Change*

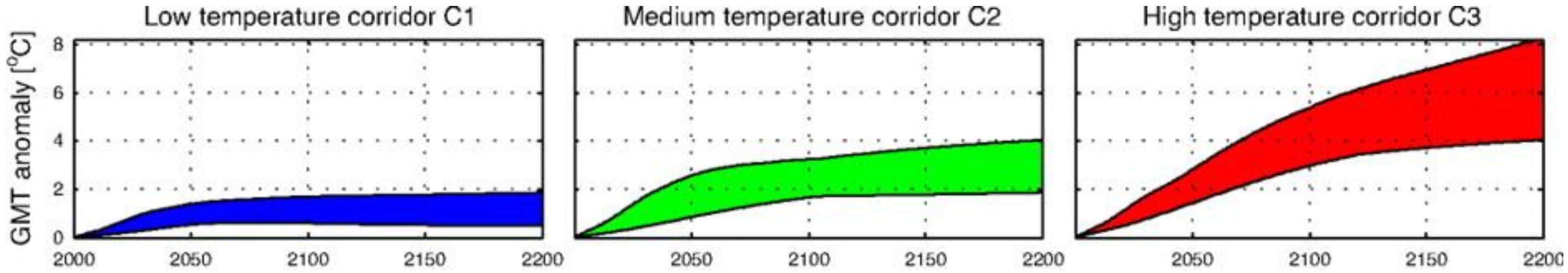


Results from literature review and workshop

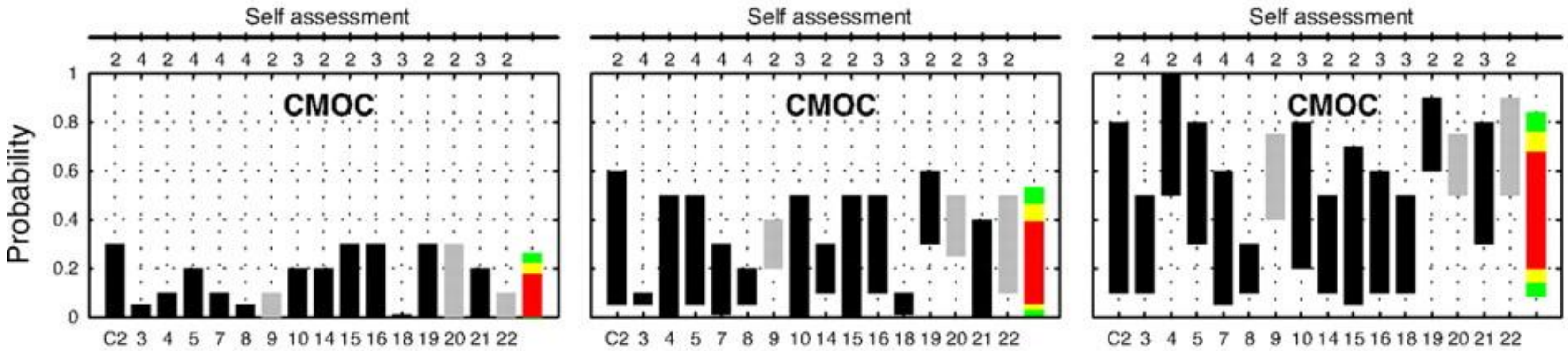
Probabilities under different scenarios

Kriegler et al. (2009) *PNAS* **106**(13): 5041-5046

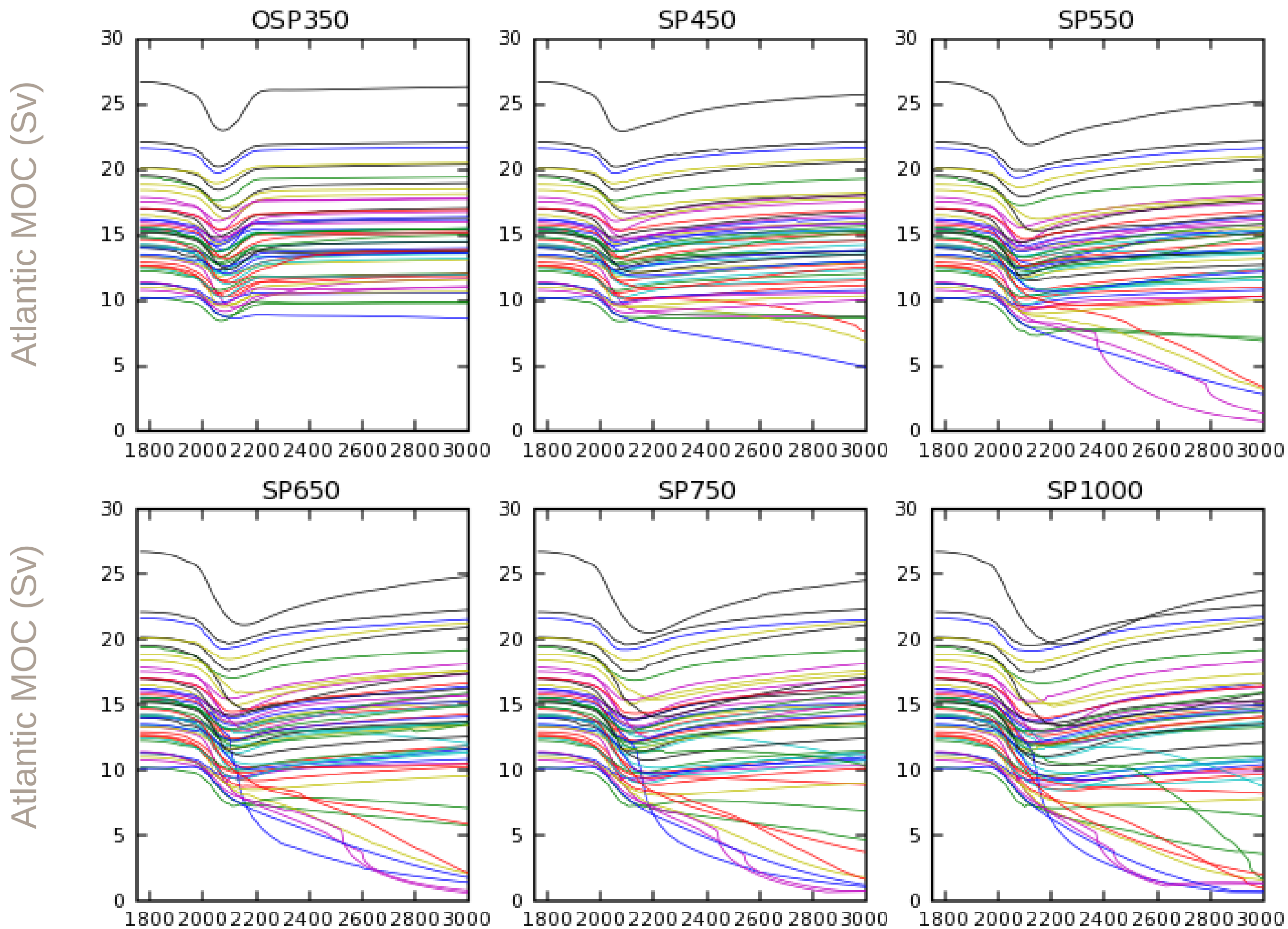
- Three different warming scenarios:



- Imprecise probability statements elicited from experts for tipping scenarios
- Example of collapse of Atlantic meridional overturning circulation:



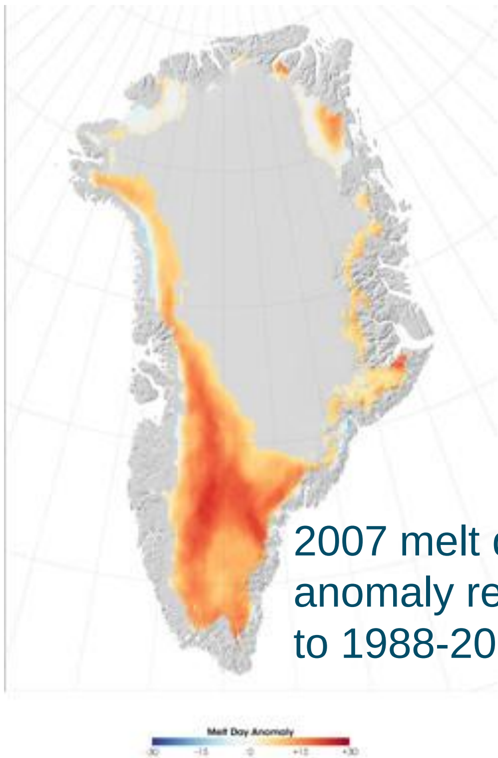
Atlantic meridional overturning circulation



GENIE-1 model, data assimilated with Ensemble Kalman Filter, for IPCC AR4, 3°C climate sensitivity

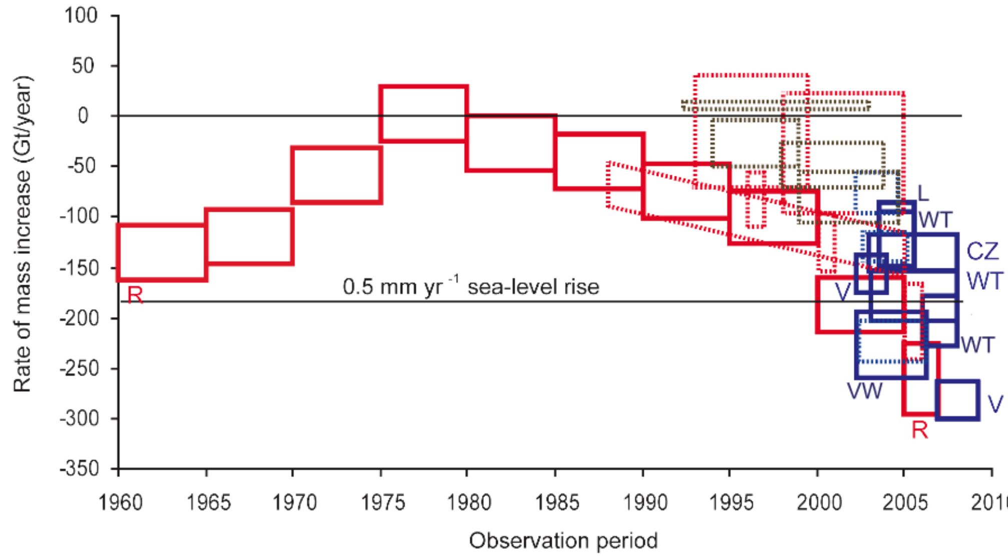
Greenland ice sheet

The Copenhagen Diagnosis (2009)

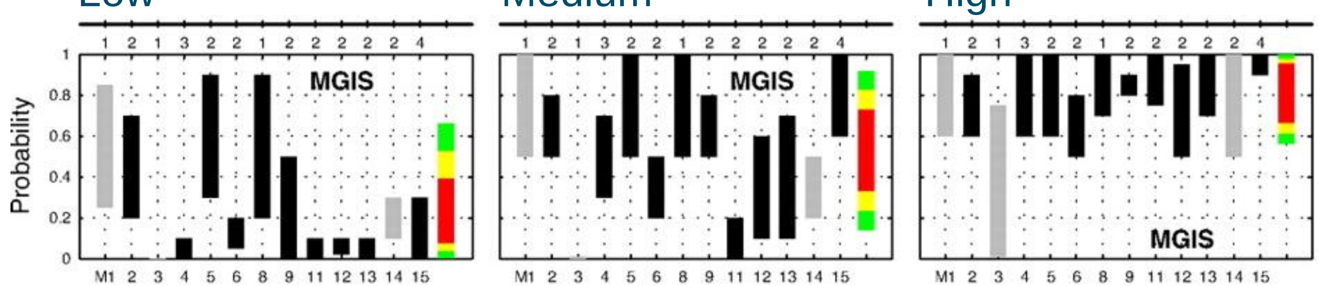


2007 melt days anomaly relative to 1988-2006

Net mass balance of Greenland ice sheet



Expert elicitation for future warming scenarios:

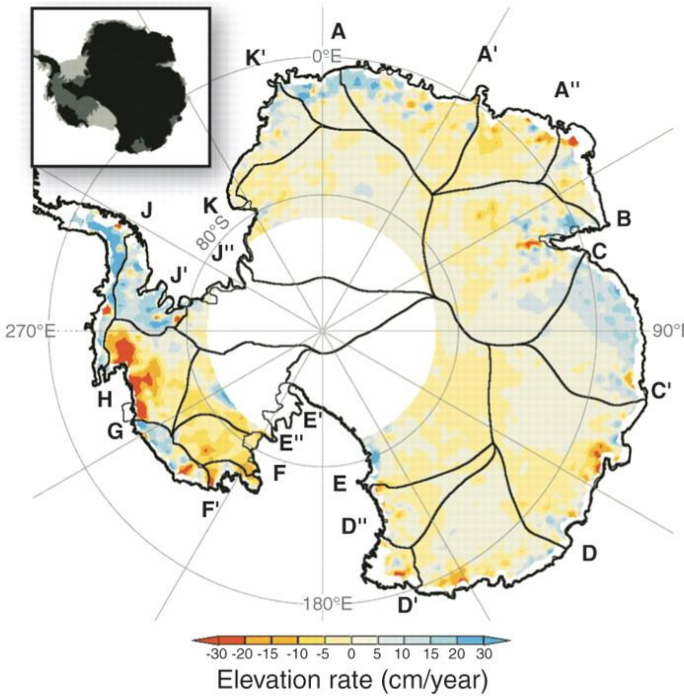


West Antarctic ice sheet

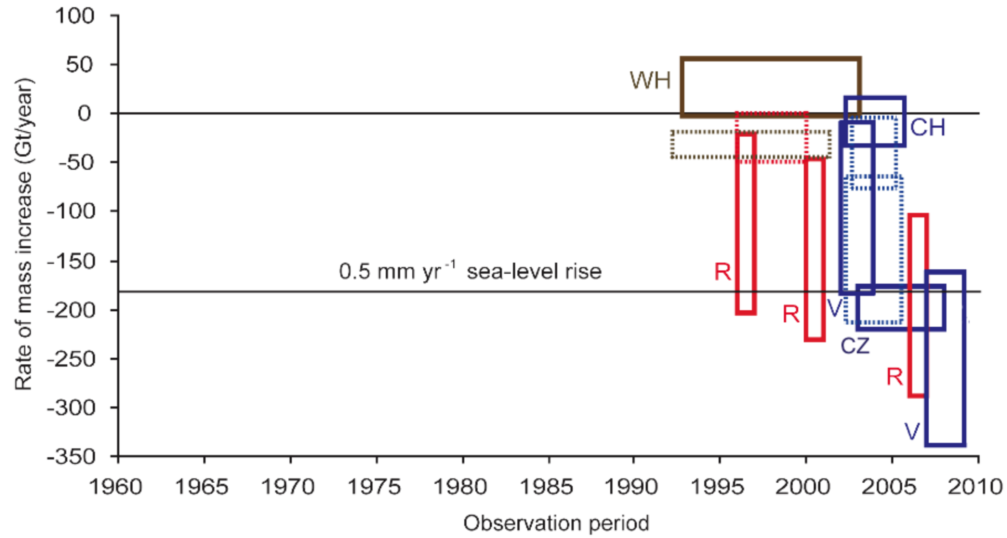
University of East Anglia

Shepherd & Wingham (2007) *Science* 315: 1529-1532

The Copenhagen Diagnosis (2009)

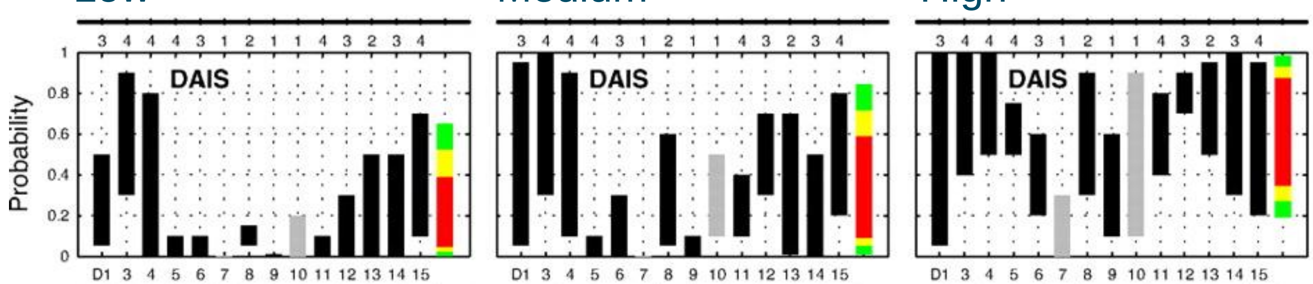


Net mass balance of Antarctic ice sheet



Expert elicitation for future warming scenarios:

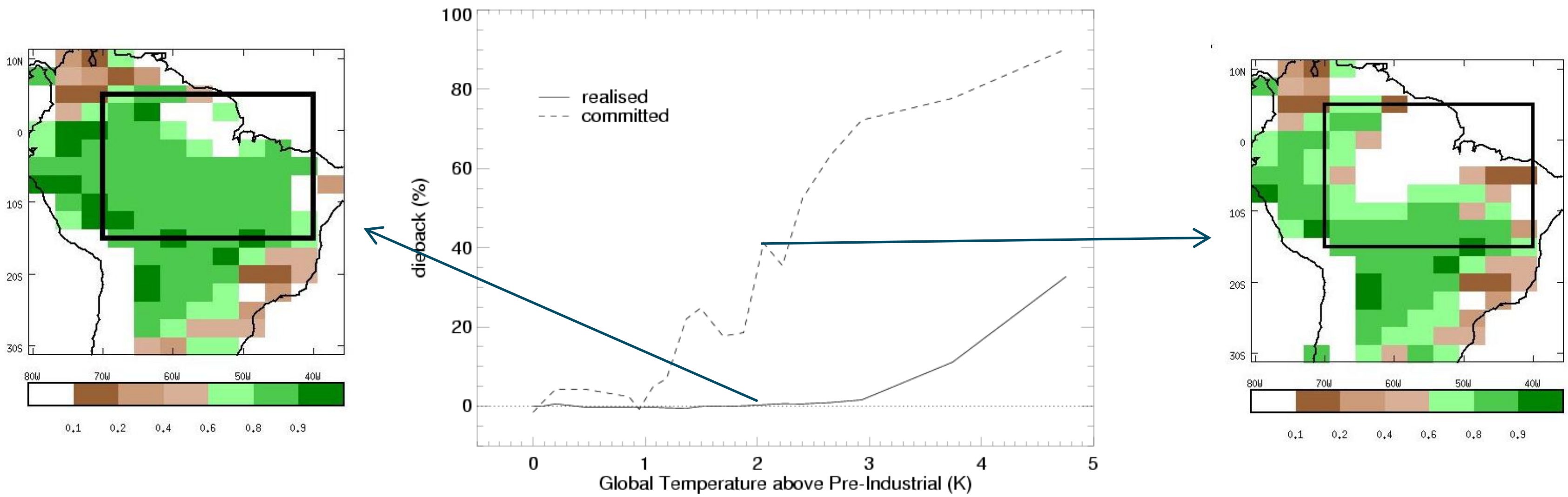
Low Medium High



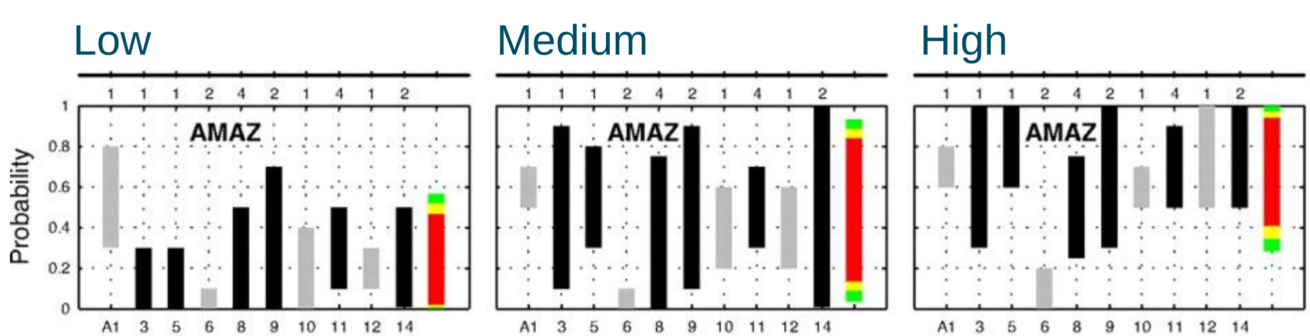
Amazon rainforest

Jones *et al.* (2009) *Nature Geoscience 2*: 484-487
Cook and Vizy (2009) *Journal of Climate*

Cox *et al.* (2000) *Nature* 408: 184-187



Expert elicitation for future warming scenarios:

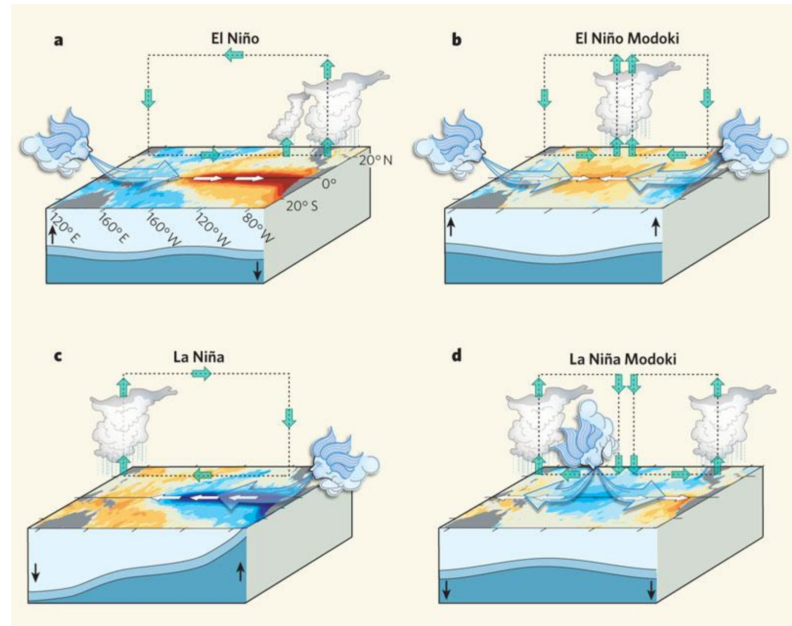


El Niño / Southern Oscillation

University of East Anglia

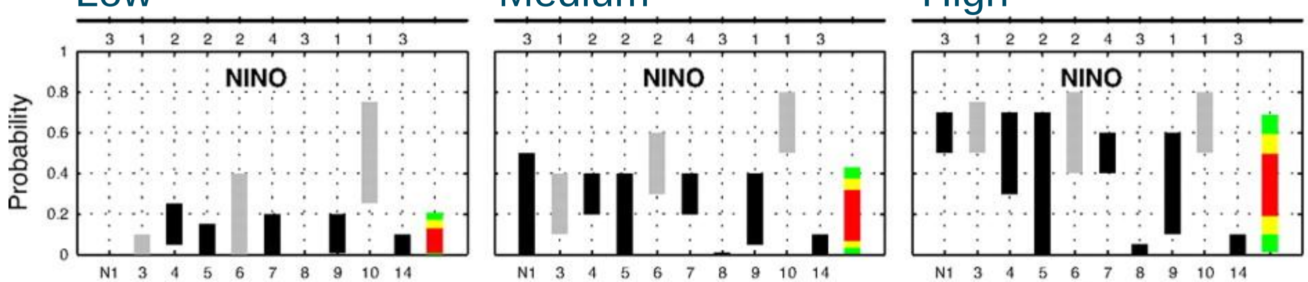
Guilyardi (2006) *Climate Dynamics* 26: 329-348, Yeh et al. (2009) *Nature* 461: 511-514

- Increase in ENSO amplitude in in most realistic models under 3-6°C warmer stabilised climate.
- No clear change in El Niño frequency
- Shift toward Central Pacific Modoki replacing classic East Pacific El Niño?



Expert elicitation for future warming scenarios:

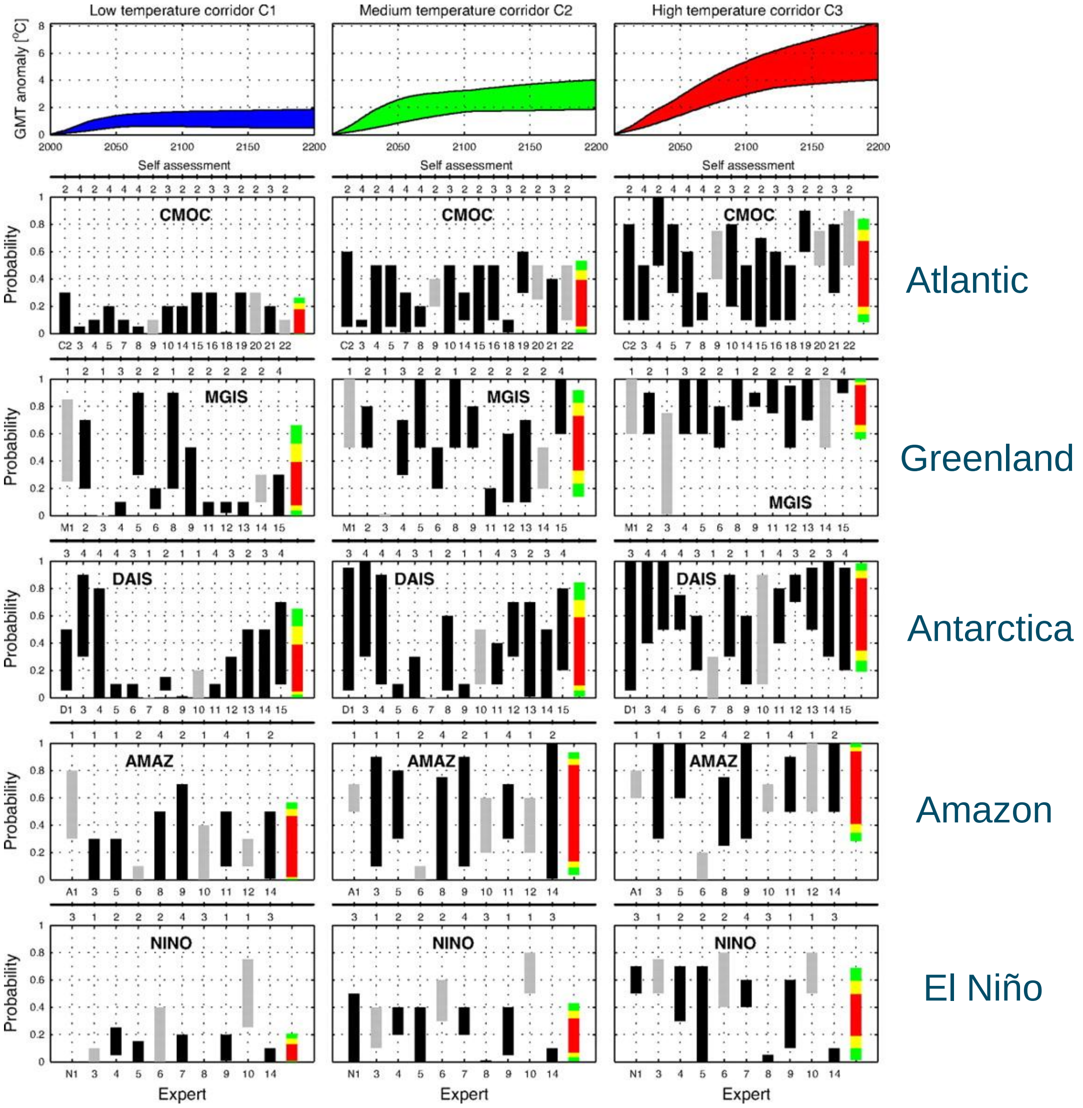
Low Medium High



Combined likelihood of tipping

Kriegler et al. (2009) *PNAS* **106**(13): 5041-5046

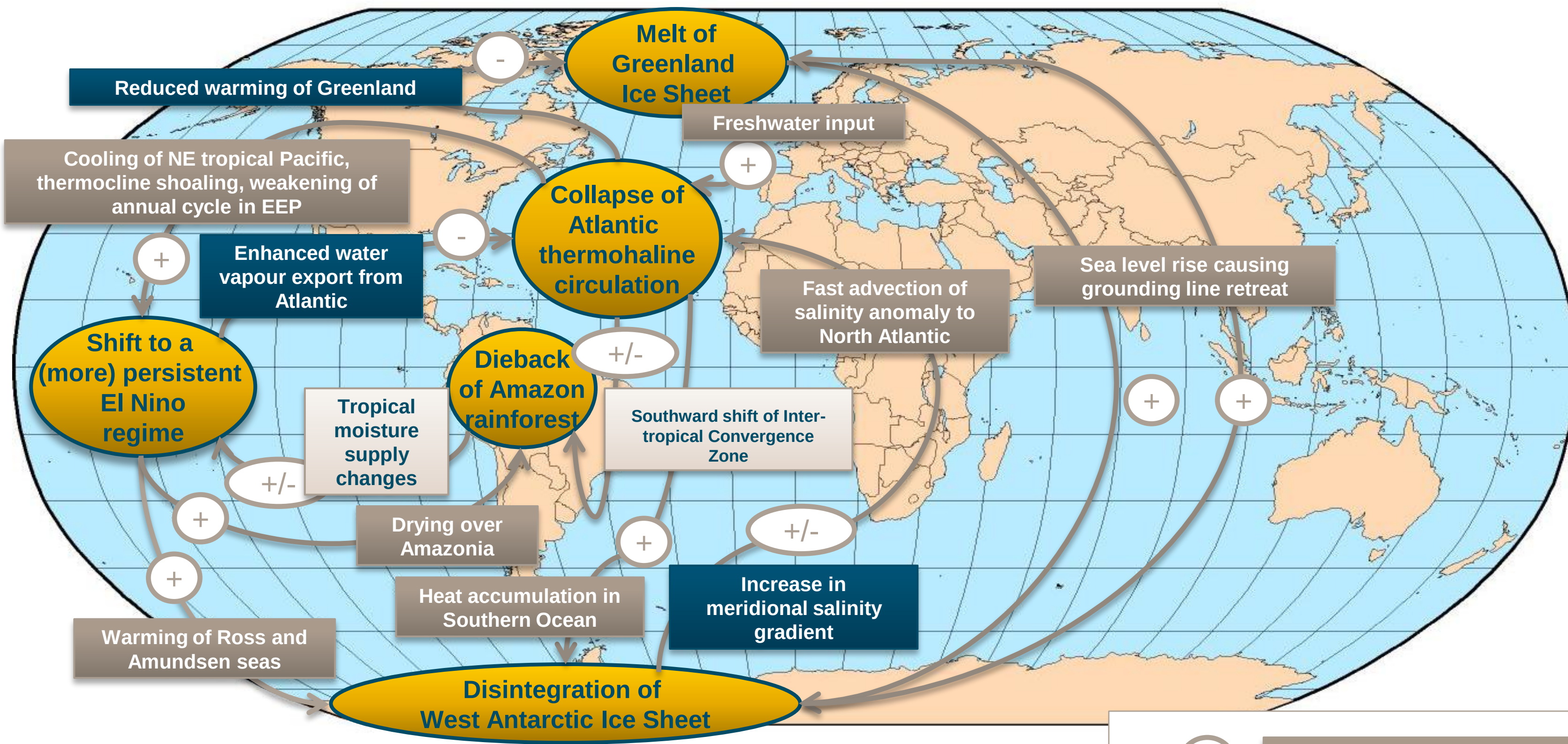
- Imprecise probability statements from experts formally combined
- Under 2-4 °C warming: >16% probability of passing at least one of five tipping points
- Under >4 °C warming: >56% probability of passing at least one of five tipping points



Interactions between tipping events

University of East Anglia

Kriegler et al. (2009) *PNAS* **106**(13): 5041-5046



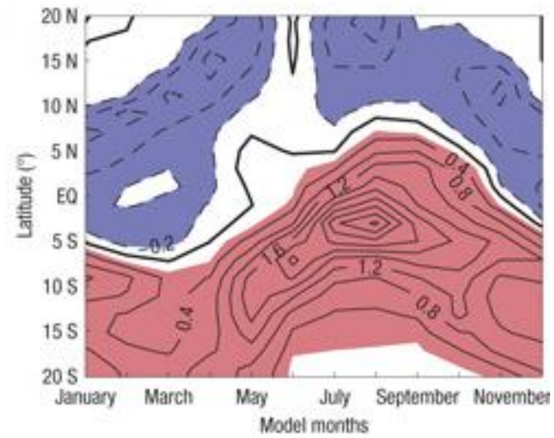
Tipping events are connected A→B if at least 5 experts judged that triggering A had a direct effect on the probability of triggering B thereafter

+	Increase in probability
-	Decrease in probability
+/-	Uncertain direction of change

West African Monsoon

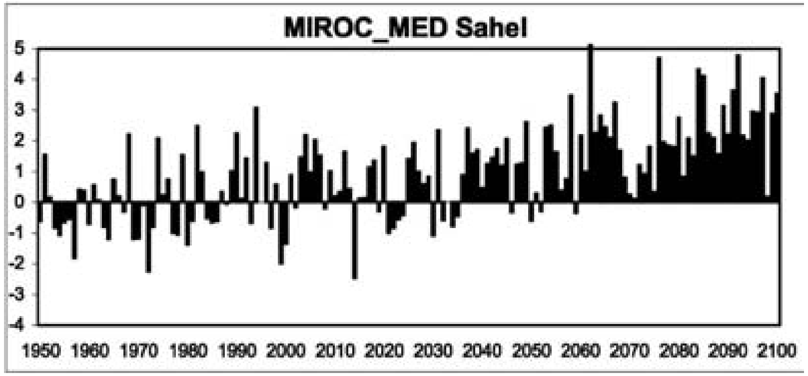
Chang *et al.* (2008) *Nature Geoscience* **1**: 444-448

- Weakening of the Atlantic overturning circulation could trigger collapse of West African Monsoon (WAM)
- Collapse of the WAM could in turn cause increased inflow of moist air from West
- Requires ~3K warming of Gulf of Guinea SSTs
- Potential for increased food production in the Sahel region



Fractional change in annual precipitation cycle

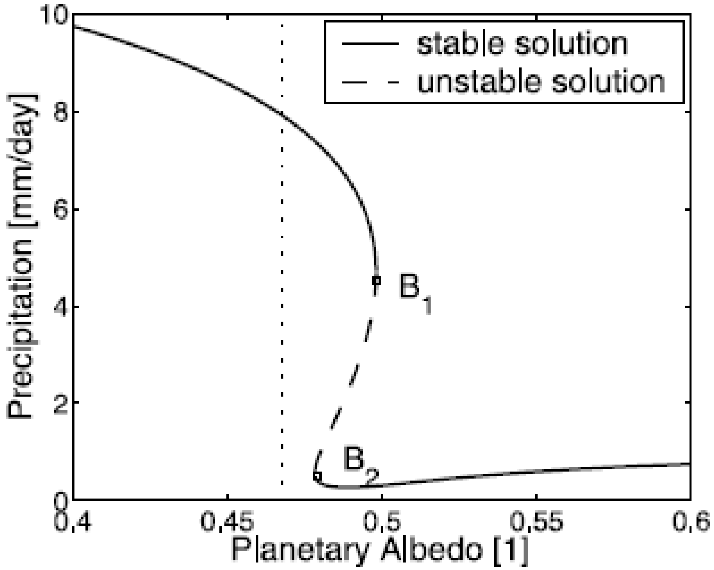
Sahelian JJAS precipitation change (mm day^{-1})

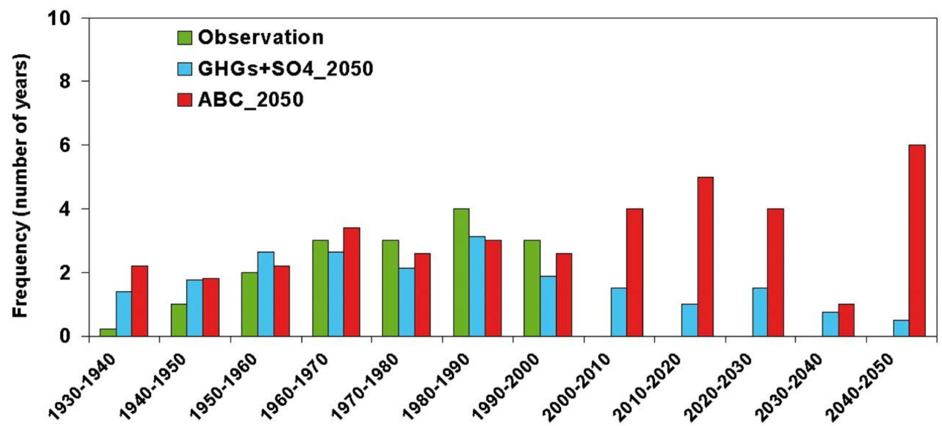


Cook and Vizy (2006) *Journal of Climate* 19: 3681-3703

Indian summer monsoon

Zickfeld, K. *et al.* (2005) *GRL* **32**: L15707; Ramanathan, V. *et al.* (2005) *PNAS* **102**(15): 5326



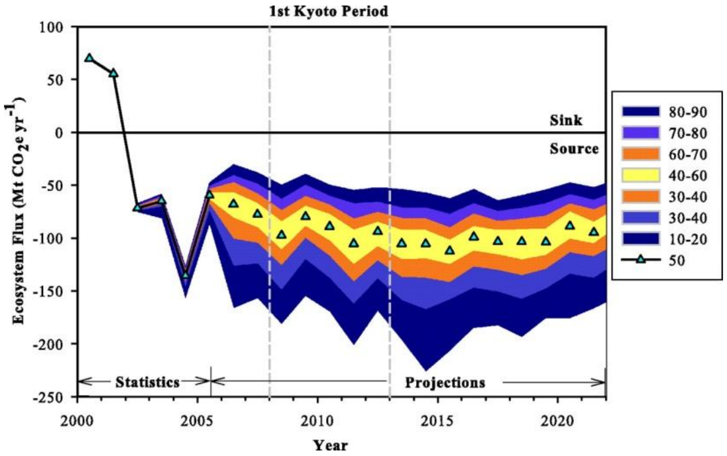


- Atmospheric brown cloud haze tends to weaken monsoon
- Greenhouse gas forcing tends to strengthen monsoon
- Potential “roller coaster” with huge societal impacts

Boreal forest

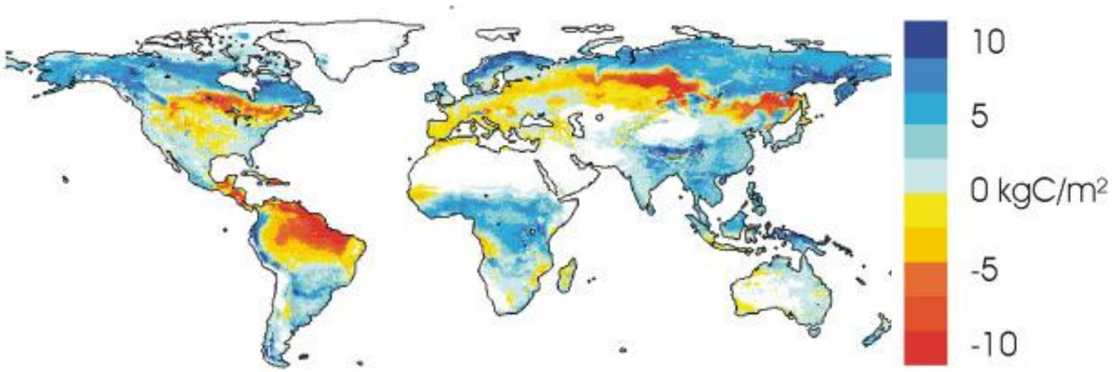
Lucht *et al.* (2006) *Carbon Balance and Management* 1: 6; Kurz et al. (2008) *PNAS* 105(5): 1551-5

- Canadian forests have recently switched from carbon sink to source due to insect outbreaks



- More widespread dieback forecast under ~3°C global warming (~7°C local warming)

- Map shows change in vegetation carbon content from 2000 to 2100
  - LPJ model forced with SRES A2 climate change from HadCM3



Yedoma permafrost

Khvorostyanov et al. (2008) *Geophysical Research Letters* **35, L10703**

- Extent of permafrost melt forecast to be proportional to warming (*not* a tipping element)

- But Yedoma, containing up to 500 PgC, could undergo runaway meltdown due to biochemical heat release

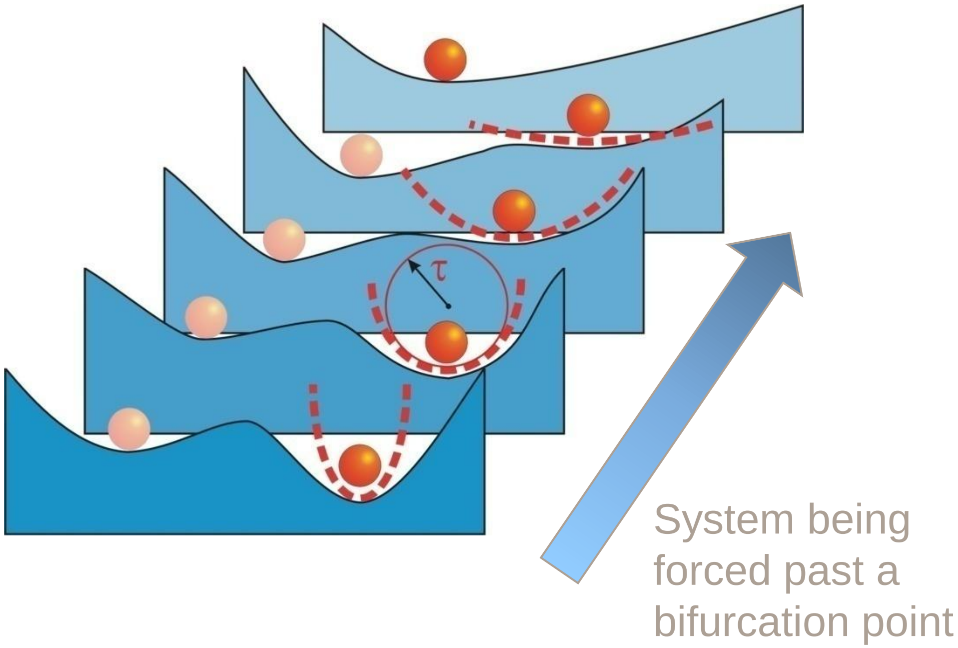
- Estimated threshold is a 9 °C regional warming, but note this region warmed >3 °C in 2007

Prospects for early warning

Held & Kleinen (2004) *Geophysical Research Letters* 31: L23207
Lenton et al. (2008) *PNAS* 105(6): 1786-1793

Generic early warning signals:

- **Slowing down**
- Increasing variability
- Skewness of responses



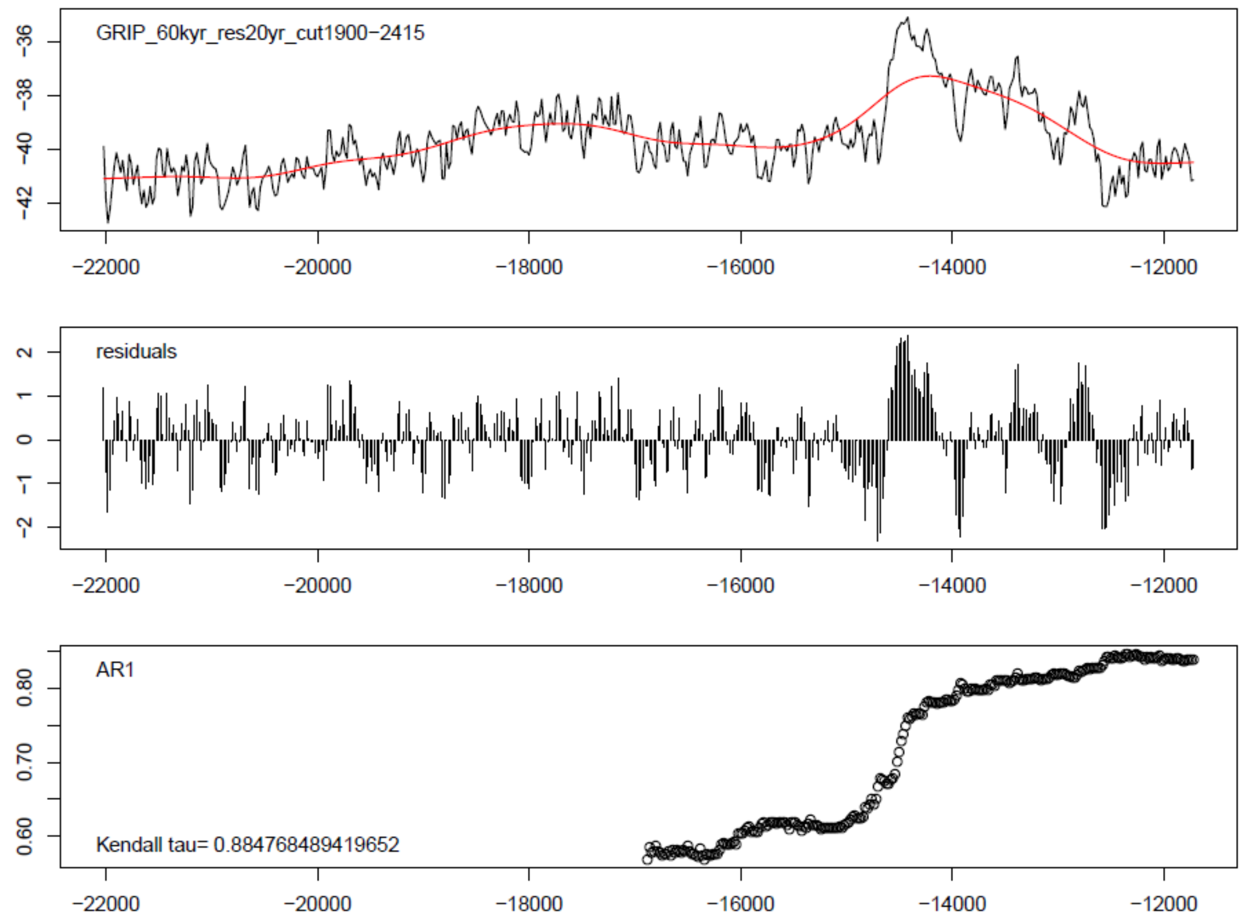
Slowing down at the end of the ice age

Lenton, Livina, Dakos *et al.* (in prep.) *Phil Trans A*

GRIP $\delta^{18}O$ data

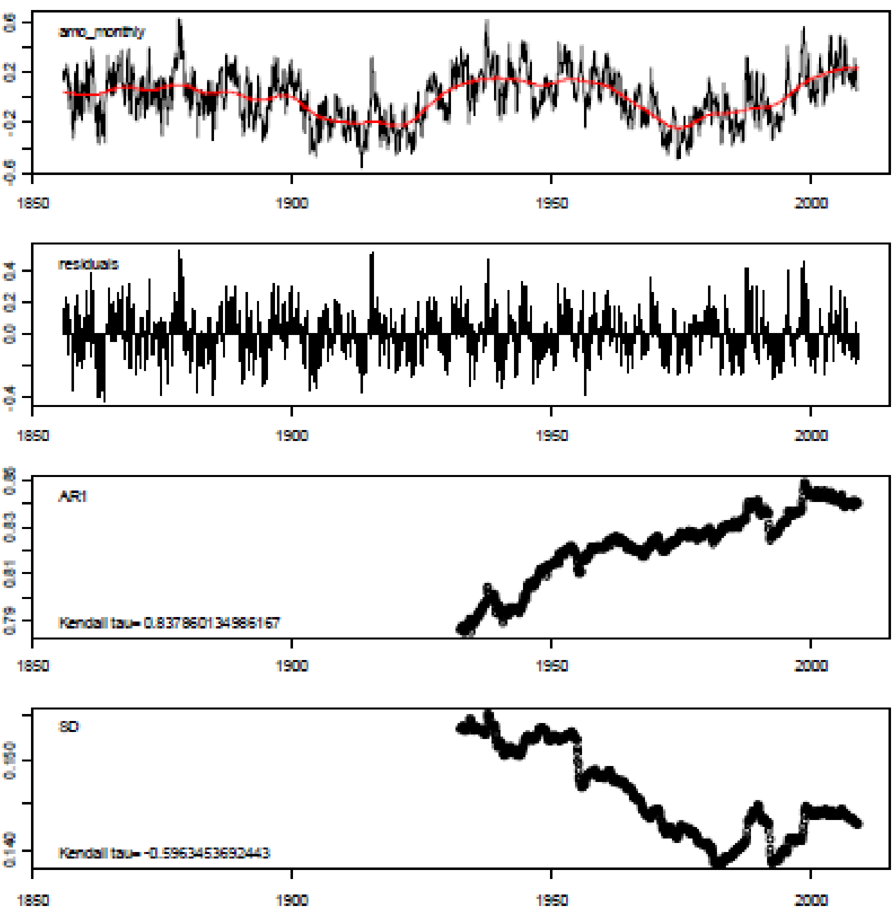
Detrended data

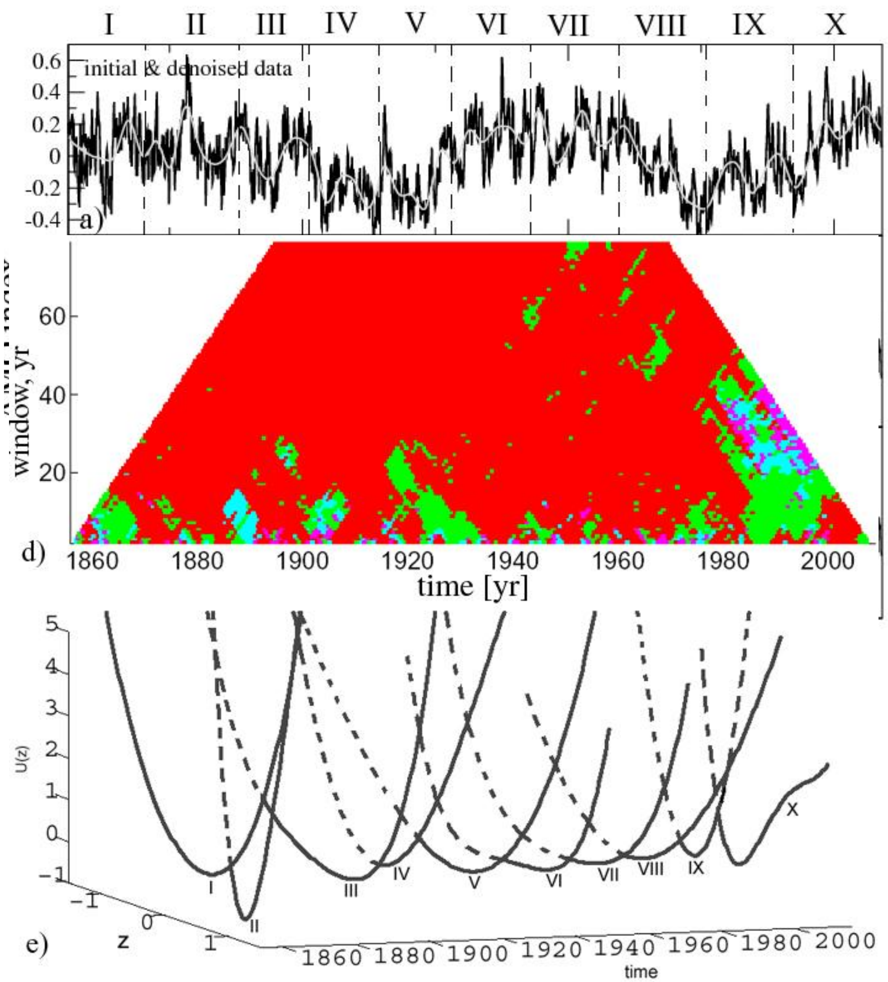
Early warning indicator



Atlantic Multi-decadal Oscillation index

Results from Vasilis Dakos and Valerie Livina





Number of states: 1, 2, 3, 4

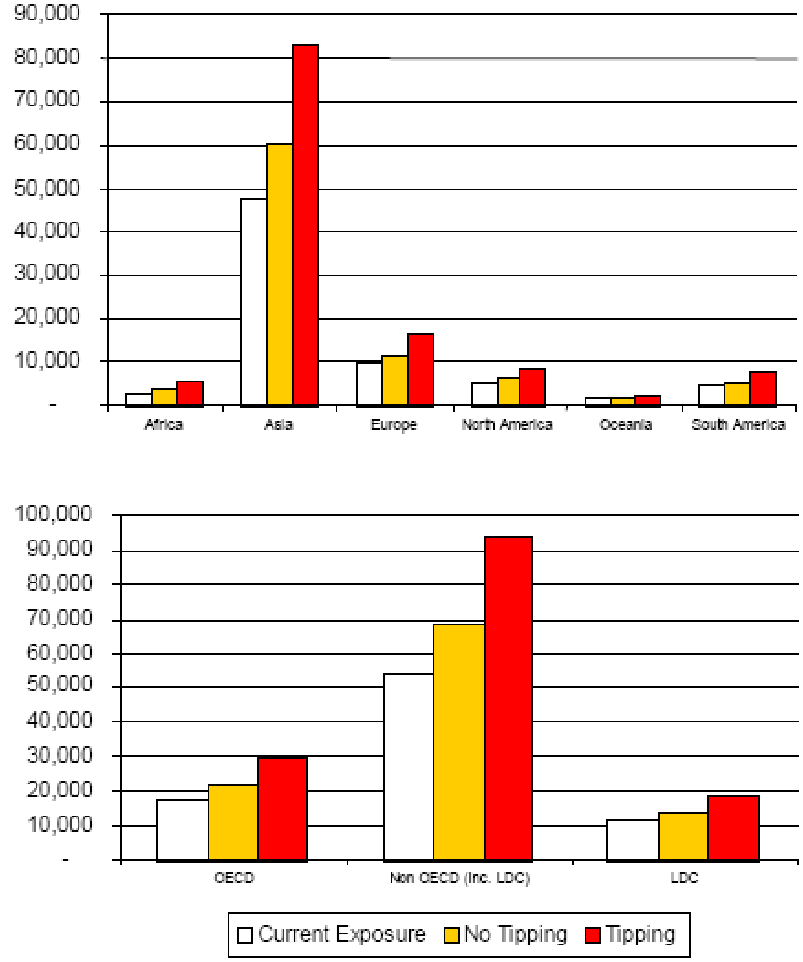
Impacts of tipping

Lenton, Footitt & Dlugolecki (2009)

Allianz / WWF report:

- Increased sea level rise
  - +$25,158 billion exposed assets in port megacities
- Amazon dieback and drought
- Indian summer monsoon disruption
- Aridification of southwest North America

Populations exposed to 1-in-100-yr flood events



http://knowledge.allianz.com/climate_tipping_points/climate_en.html

'Straw man' tipping point risk assessment

University of East Anglia

Tipping element	Likelihood of passing a tipping point (by 2100)	Relative impact** of change in state (by 3000)	Risk score (likelihood x impact)	Risk ranking
Arctic summer sea-ice	High	Low	3	4
Greenland ice sheet	Medium-High*	High	7.5	1 (highest)
West Antarctic ice sheet	Medium*	High	6	2
Atlantic THC	Low*	Medium-High	2.5	6
ENSO	Low*	Medium-High	2.5	6
West African monsoon	Low	High	3	4
Amazon rainforest	Medium*	Medium	4	3
Boreal forest	Low	Low-Medium	1.5	8 (lowest)

*Likelihoods informed by expert elicitation
**Initial judgment of relative impacts is my subjective assessment

Conclusion

University of East Anglia

- Tipping elements in the climate system could be triggered this century by anthropogenic forcing
- If business-as-usual continues we should expect to pass tipping points, i.e. high impact *high* probability events
- Early warning systems are conceivable and could help societies manage the risk posed by tipping points
- More research is needed on the corresponding impacts in order to do a proper risk assessment
- Then put that data in your integrated assessment model!

October 25, 2010 version

CATASTROPHIC CLIMATE CHANGE

Mike Toman, World Bank Development Research Group

Draft, subject to revision; please do not cite or quote. Responsibility for content is the author's alone.

INTRODUCTION

The question of how to assess prospects of climate change catastrophes has been the focus of a great deal of recent research and debate. An example of the classic conundrum of low probability – high consequences events, a climate change catastrophe is a highly unlikely event, but if it did occur it would severely affect well-being across the world – though it would affect poor countries much more seriously than richer countries.[1] The larger geographical scale of climate change catastrophes distinguishes them from more localized extreme events. The consequences of catastrophes also are in varying degrees very costly, if not possible, to reverse.

Examples of global catastrophes include very large and relatively rapid increases in sea level from faster melting and collapse of ice sheets, slower changes in ocean currents that have insidious effects on weather patterns, and large scale destruction of forests and other ecosystems. fairly rapid loss of global forest cover. Unlike sudden disasters such as earthquakes, the onset of these events is measured in multiple decades or centuries; but once they occur it is impossible to reverse the impacts. Other permanent effects of climate change are anticipated to be increases in the frequency and severities of droughts, floods, and hurricanes, leading to corresponding destruction of crops, water supplies, and coastal infrastructure. While each of these individual events is a more localized disaster, the cumulative effect could be a global catastrophe created by the "cascading consequences" of more localized disasters occurring in relatively quick succession, each amplifying the effects of others.[2]

A key step in evaluating risks of climate change catastrophes is to assess not only the impacts on the physical climate system, but also the consequences in terms of human impacts. The most immediate implication is that while a physical "tipping point" may be reached at some unknown future date T^0, the human impacts will evolve more slowly, reaching an intensity viewed as catastrophic only at some date $T^1 > T^0$. This distinguishes climate change from, for example, the risk of catastrophe posed by a gigantic volcanic eruption, or nuclear war. While a gradual onset of impacts will not prevent a catastrophe if reversal is not possible, it can provide a window of time for major action to avert or adapt to the threat – if signals of the changes are detectable. More fundamentally, the assessment of what constitutes catastrophic human impacts involves not just climate change and earth system science, but also inherent value judgments about what magnitude and speed of consequences are deemed to be catastrophic. For example, the now-often-cited "scientific near-consensus" about the urgent need to hold warming to less than 2°C relative to pre-industrial times reflects more than a natural science evaluation of climate change impacts.

Climate change catastrophes pose a familiar challenge for assessing the impacts of low probability – high impact events: while exact quantification is not possible, the most extreme adverse impacts from climate change—say the worst 1% of scenarios—may account for a large portion of losses in expected value terms. This implies that focusing primarily on a trajectory of more likely anticipated climate change

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[1] In terms of absolute numbers, losses are likely to be larger in richer nations. As a percentage of GDP, however, less developed countries are likely to face higher damages since most are more dependent on agriculture and less likely to have the resources to adopt measures that could reduce damages.

[2] This possibility appears to have received little systematic attention in reviews of climate change impacts by the IPCC and others, though it figures prominently in discourse about national security consequences of climate change.

damages may miss an important part of the problem.[3] Yet, these consequences of an unlikely but possible climate change catastrophe need to be weighed against a variety of other risks society faces.

Further complicating the problem is that climate change catastrophes may be better characterized by ignorance than uncertainty. That is, not only do we not know the probability of a particular mega-catastrophe occurring, we do not even know many of the possible outcomes. A catastrophe from climate change could stem from a cause or have impacts that currently receive little attention.[4] Some authors have suggested that this level of ignorance, coupled with the very low probability of an event and the possibility of extremely severe impacts, hamstrings the use of rational-choice based methods for analyzing response options. This in turn requires confronting the possibility that attitudes of the broader public about such events will not align very well with the results of a more systematic evaluation of the pros and cons of different response options, raising questions about what sets of preferences and beliefs should govern policy making.

CLIMATE CHANGE CATASTROPHES

The most widely discussed large-scale impact of climate change is **global sea level rise**. The collapse of the West Antarctic Ice Sheet (WAIS) or Greenland ice sheets could lead ultimately to a sea level rise of several meters, with consequences great enough to be considered a global catastrophe in the absence of massive and costly relocation because of the number of people living near the coasts. A key uncertainty is how rapidly this change in sea level might occur. Previously it had been thought that such large changes might require much longer than a century, but some recent studies suggest that substantial change could occur in this century. Anthoff et al. (2009) report figures for world losses (based on 1995 baseline conditions) that are relatively small – on the order of 0.5% of world GDP for a 5 m rise. Dasgupta et al. (2007) report figures for developing countries on the order of 6% of GDP, those these estimates do not take account of possibilities for ex ante efforts to mitigate risks. On the other hand, estimates based on historical baselines will tend to under-state the economic impacts of sea level rise by not taking account of likely future growth in the coming years in the share of GDP concentrated in coastal areas.[5]

A second important category of global catastrophe risk involves **disruptions of ocean circulation from climate change,** with potentially disastrous effects on regional weather patterns and long-term climate (Vellinga and Wood 2008). Such impacts are most commonly seen as developing over many hundreds of years. In contrast, **very large-scale ecosystem disruptions** could occur significantly sooner. Changes in ecosystems resulting from changes in temperature and rainfall incidence and increased climate variability have the potential to cause very significant loss of biodiversity—on the order of 20-30% extinction within a few decades. There is also the prospect of major changes in vegetation, in particular, irreversible

[3] For many classes of disasters and catastrophes, the most extreme small percent of the situations represent a significant proportion of the losses. We have witnessed this "fat tail" phenomenon recently with terrorist deaths and losses in a financial crisis. 9/11 and the 2008-09 financial meltdown caused more deaths and dollar losses respectively than all terrorist incidents and financial catastrophes in the post WWII era. With such phenomena, losses are better characterized by a power law than by a normal or even lognormal distribution. The debate about fat tails in relation to climate catastrophes has been a subject of lively recent debate among Weitzman, Pindyck, Nordhaus, and others.

[4] The history of the past 40 years is sobering with respect to the ability to identify catastrophe risks. In 1970, nuclear war would have been the leading contender for any world catastrophe, and looking forward few would have predicted the major looming threats of the current era, which would include not just climate change, but also global pandemics and terrorism.

[5] Using 1995 data, it has been estimated that around 400 million people would be impacted by a 5 m rise in sea level and that a WAIS collapse in 100 years could cause, at the peak, 350,000 forced migrations a year for a decade (Nicholls, Tol and Vafeidis 2008).

conversion of forest to grassland, desertification, and acidification of the ocean (Smith, Schneider, Oppenheimer et al. 2009). Another cause for significant concern is the possibility that positive feedback effects in the climate change process itself could occur (e.g., liberation of trapped methane from ice, rapid increases in CO_2 from vegetation dieback, or increased heat absorption as glaciers retreat), causing the abovementioned changes to occur more rapidly.

There also has been significant scientific research on how climate change can effect more localized disasters, such as heat waves, flooding, droughts, and changes in hurricane frequency or intensity. Less understood is how **a number of smaller disasters** all occurring over a relatively short time period could mutually reinforce each other in such as way that the **resulting "cascade of consequences" becomes a global catastrophe**. Extreme events can have secondary consequences that generate substantial amounts of additional damages; secondary consequences in turn can trigger tertiary consequences that further amplify the adverse consequences; and so on. One example would be if increased drought from climate change in different regions successively caused a series of local food shortages to occur in close proximity, leading to political instability, a breakdown of civil order, large-scale migration for survival, and regional conflicts. Another example could be a series of local fires occurring in climate-stressed forests and grasslands overly widely dispersed areas, adding up to a large-scale destruction of resources, ecosystem services, and livelihoods over a large area.

The compounding or amplifying effects of individual adverse impacts would be the result of exceeding the resilience of a number of local socioeconomic systems in rapid succession. More frail components of socioeconomic systems, such as marginal subsistence agriculture, represent potential places of vulnerability. Cascading-event catastrophes could occur much more rapidly than the slower-onset global impacts discussed above, especially as climate change accelerates and greater negative impacts occur at local scales. It is possible that more comprehensive local monitoring of disaster risks may facilitate the development of early warning indicators for cascading catastrophes. For example, if several years of historically unusual drought weakened agricultural systems in many vulnerable parts of the world, there would be a stronger basis for concern about cascading consequences than if agricultural failures were not occurring in such rapid succession. However, the time interval for action to avert the potential catastrophe could be short.

Traditional responses to the risk of extreme events are of limited value in mitigating risks of a mega-catastrophe. The underlying changes in the climatic system could not be reversed over any time scale relevant for decision-makers. Traditional insurance mechanisms will not function effectively for this type of event, because the risks are "systemic" and cannot effectively be reallocated to diversify. Moreover, significant international transfers from richer to more vulnerable poorer countries are unlikely when a catastrophe affects broad swaths of the world.

EVALUATING CLIMATE CHANGE CATASTROPHE RISKS

The traditional economic model for decision making under uncertainty is expected utility theory, in which decision makers maximize the utility they receive from potential outcomes weighted by the probability the outcomes will occur. In the climate change economics literature, GHG abatement policies with the expected net benefits over time are identified using dynamic Integrated Assessment Models (IAMs) that compare the anticipated costs of abatement with avoided damages from climate change over time. By and large these models are deterministic and are used for scenario-based comparisons of policies under different assumptions about climate change damages and abatement costs. However, a literature has developed in which catastrophes are treated as (usually known) large-scale rapid-onset economic damages with an uncertain date of occurrence, the probability of which increases as atmospheric GHG concentrations rise.[6]

A common finding in these studies is that while the risk of such catastrophes increases the expected economic benefits of more rapid GHG mitigation, the effect is not that significant qualitatively unless the probability of nearer-term catastrophe is quite high, the size of the catastrophe is truly astronomical, or the discount rate used to value future catastrophic impacts is quite low. The scientific information on catastrophes summarized above indicates that catastrophes are extremely unlikely in any time frame short of several decades at the very least, and that while the ultimate effects may indeed be huge, the most severe impacts will develop only gradually. Until scientific understanding of climate change catastrophes leads to stronger findings on their proximity and severity, the choice of discount rate will be the most important determinant of the cost of future catastrophes in the expected-utility framework.

The discount rate issue in turn continues to be very hotly debated, and only a very brief summary of key points is offered here. Two strands of positive analysis has argued for applying a lower discount rate to longer-term climate change costs, including catastrophes, than might be inferred from research on consumer time preference or rates of return on investment. One is that individuals may discount the future hyperbolically, so rates of discount decline and ultimately plateau at a fairly low number as one goes out into the future. The other is that when one accounts for the higher marginal utility of income for the poor facing more adverse impacts from climate change, then under reasonable assumptions the effective time discount rate after adjusting for distributional differences is reduced. In addition, if climate change has the most severe effects on longer-term economic growth when growth itself is more likely to be weak, then policies to reduce the threat of catastrophe will have a lower effective discount rate because of their contribution to reducing intertemporal economic risk.[7]

Even with these considerations, however, the resulting implied discounting of future over current returns may not be small enough for catastrophes to carry major weight in evaluating the potential impacts of climate change. Unless the discount rate is under 1%, and perhaps even close to zero, severe future consequences that will not arrive for some time and are not world-threatening may still be too "telescoped." Stern and others have addressed the issue of discounting by using normative arguments to suggest a discount rate at or near zero is in fact appropriate. Two other arguments, not so dependent on normative precepts, may also add weight to the importance of catastrophe risks in evaluating climate change impacts.

Hypothesis 1: People are Not Expected Utility – Maximizers

There is a growing literature from behavioral economics and psychology which demonstrates that individuals do not consistently make decisions according to the expected utility paradigm.[8] If individuals are only boundedly rational, they have neither the time nor the capacity to fully assess the consequences of decisions. In that case, individuals adopt certain rules of thumb and mental shortcuts to make decisions. These so-called heuristics can lead to choices that depart from predictions of expected utility theory.

[6] References – Kverndokk et al, Pizer, Nordhaus. Earlier foreshadowing by Manne.
[7] [add references] Strictly speaking, the second and third arguments are not about the actual rate of time preference, but rather about how factors related to distributional impacts and risk that enter the maximand of the intertemporal utility calculation affect the implied discounting of future over current returns.
[8] This discussion is taken from Kousky et al (2009), which contains references to the relevant behavioral economics literature.

When thinking about possible disasters, it has been found that people tend to be over-optimistic, thinking negative outcomes are less likely to happen to them. When a risk is highly emotional, however, people can disregard probabilities altogether, treating all outcomes as equal ("probability neglect"). Individuals also seem to place an added value on certainty, preferring to reduce a small risk to zero by more than they value reducing a larger risk by a greater amount. Errors of commission are viewed as worse than errors of omission. This can lead to a tilt to the side of inaction.

Experimental also has found that context matters, often significantly, a when making decisions. For instance, when probabilities are unknown and must be estimated, individuals have been found to assess an event as more likely when examples come to mind more easily (the "availability heuristic"). People can disproportionately prefer to maintain the status quo in their choices, even if conditions or options change. Individuals sometimes "anchor" their preferences on an available piece of information, and fail to update their assessments adequately in the face of new information. Individual choices are also strongly affected by the way that information is presented. Thus, individuals may make different choices for the same decision if it is merely phrased differently ("framing effects"). Choices depend upon the extent to which a risk evokes feelings of dread. Personal utility also is sensitive to individuals' perceptions of equity and fairness.

These various behavioral attributes can imply higher or lower values attached to catastrophe risks than would be implied by expected utility theory. The former would follow from dread or the evaluation of all catastrophes as roughly equal in likelihood. The latter would follow from optimism bias, or a preference for reducing small and familiar risks to zero over reducing more substantially an unfamiliar risk – of which climate change catastrophe certainly is an example. While the direction of bias has to be assessed empirically, the existence of these various "non-rational" attitudes raises an important but not new question for evaluating climate change catastrophe risks in setting public policy: if decision makers believe they have better information than the general public and that they are less subject to emotional biases, to what extent should their valuation of alternatives supersede those of members of the general public?

Hypothesis 2: People are Non-Egoistic Expected Utility – Maximizers

A second approach that has been taken in the literature for addressing long-term threats posed by climate change is to see individuals today, imperfect information and all, as interested in more than maximizing the discounted present value of their lifetime expected utility streams. One can broadly define this as altruistic preferences, but this label can cover several different forms of preferences.

A traditional approach to altruistic preferences is to include some measure of next-generation or other future utility in the preferences of members of the current generation. In this setting, individuals will weigh the potential costs of a climate change catastrophe in terms of its anticipated impacts on future welfare, as well as the possibly slight impact on current individuals' egoistic well-being. Consequently, individuals will derive utility in part from the "bequest they leave to the future in terms of a lowered (endogenous) risk of a climate change catastrophe. However, there are both theoretical and empirical reasons to expect individuals to discount the welfare of future generations relative to their own egoistic welfare. This takes us back to the question previously mentioned in the context of time preference, as to how powerful an influence this form of altruism might be in the current generation's assessment of risks of climate change catastrophes.[9]

A second approach is to depart from a purely utilitarian framework by supposing that individuals see themselves (or should do) as having a moral obligation to future generations. This mixing of obligations and conventional utilitarian motivations implies some degree of lexicography in individuals' preferences – or, critics of utilitarianism might say, an innate failure of the standard economic model to describe what really motivates people. In this view, if a potential future catastrophe threatens to impose a morally inacceptable burden on the future, people will be (or at least can be) motivated to endure potentially extra-ordinary sacrifices to reduce the threat. The expression of that moral sentiment by individuals as citizens and stewards, versus utilitarian consumers, would be found through public choice exercises like voting for tough restrictions on future GHG emissions.

This conception is both stimulating and frustrating, since it does not offer any straightforward way of assessing how economically significant is the threat of a future climate change catastrophe. Aside from uncertainty about what the triggering level of threat to the future might be, does one regard current almost universal reticence to support tough GHG restrictions as due to (correctable) moral failing? Lack of information? Lack of leadership? The result of rational leadership, because the threat of climate change is seen as less significant than other threats or because international collective action problems have not been solved?

A third possible approach that has received less attention is that individuals have preferences that include some notion of "planetary health" as a global public good. Rather than seek to describe concern about risks of catastrophe from climate change as deriving only from more fundamental concerns for intergenerational altruism or fairness, one could posit that individuals derive some direct benefit from having greater confidence in the ability of planetary systems to remain undisrupted, without the need to unpack the rationales in terms of future human well-being, satisfaction of moral sentiment, or a pure existence benefit. This approach allows one to sidestep some of the difficulties encountered in either the altruistic utilitarian or moral-obligations conceptions. In particular, the normative approach to setting discount rates can be embedded in a framework of preferences without having to be an ad hoc add-on.[10] However, this does not get around the huge empirical problems in assessing the value that members of the current generation might place on reducing risks of future climate change catastrophes. [11]

CATASTROPHE RISKS AND RATIONAL CHOICE APPROACHES TO POLICY

While it is certainly possible to debate the capacity of expected –utility types of analyses to adequately capture the social opportunity cost of climate change catastrophe threats, it is in cases like this that a disciplined application of rational-choice based analysis more broadly defined can prove most useful. A

[9] Current individuals also could believe, as Schelling for example has suggested, that other kinds of bequests to the future would have higher value; or they could further discount bequests of a less risky climate out of concern that unless the "chain of obligation" is maintained, something impossible to assure, the sacrifice made today would be wasted in the future.

[10] A fundamental criticism of conventional expected-utility analysis for assessing future climate change risks is that it combines conventional time-preference considerations in assessing the opportunity cost of reducing threats with the explicitly ethical question of how much the current generation will feel willing or bound to do in protecting the future.

[11] Ideas like this arise often in literature on environmental stewardship, but I am not aware of many treatments of the idea in economic terms. One example is the paper by Kopp and Portney [ref to add], who describe a thought experiment in which individuals value "well being of the future," and the willingness-to-pay for that value can be discerned through a stated preference valuation effort. While one can debate the merits of the valuation approach even in a thought experiment, the concept is very similar to what I am trying to describe here. Unfortunately, the question of how one would ascertain such valuation remains a barrier to empirical implementation of the concept.

thoughtful, systematic, and transparent weighing of benefits and costs, broadly defined, is at the heart of such an approach. The presence of "deep" uncertainty or ignorance about the types and likelihoods of potential catastrophes means that we must include, in addition to sensitivity analysis on these characteristics, focused analysis of the robustness and flexibility of options in addition to the benefits and costs. With respect to what seem to be behavioral biases in the assessment of catastrophe risks by individuals, decision makers must make (and then defend) informed judgments on behalf of those they serve as to when the seeming biases reflect a high degree of economic risk aversion, or dread, and when the biases reflect other factors (framing effects, optimism bias, and the like) that can be viewed as inaccurate comprehension of the tradeoffs involved.

Posner (2005) argues that uncertainty over benefits and costs should not prevent using the basic structure of cost-benefit analysis for evaluating and comparing options, but that this should be framed in a "tolerable-windows" approach. This involves using a range of plausible risk estimates to help identify levels of spending on reducing risk for which benefits clearly exceed the costs, for which costs clearly exceed benefits. Policies then can be designed with the goal to remain in this window.[12] This approach does not provide or depend on "a number" for how to evaluate the impacts of potential future climate change catastrophes. In particular, it does not treat them as largely irrelevant economically given their low probabilities and long time frames to be realized. Instead it provides flexibility as to how different considerations about climate change catastrophes are brought into the assessment, including risk aversion and concerns about future sustainability as well as costs of risk mitigation, while insisting on transparency and a persuasive argument for how these considerations are to be addressed.

[12] This idea is akin to value-of-information approaches. If one has some confidence in the evaluation of costs of different policies but great uncertainty about the potential benefits, one could investigate how large the potential benefits might have to be to make a case for the selection of one set of options over another in a portfolio. Similarly, if the benefits are reasonably well understood conditional on a catastrophe occurring, but there is uncertainty about the probability of a catastrophe, then one can ask how large the probability would have to be to justify a particular portfolio of actions.

Social Cost of Carbon and Risks of Climate Change Catastrophes

Mike Toman

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EPA Climate Change Impacts Workshop

November 19, 2010

Views are the author's alone

Interest in the Topic

- Concern that "tipping points" may be closer in time and more serious than had been anticipated
  - calls for rapid and deep cuts in GHG emissions
- Concern for the uncertain fate of international negotiations
  - mitigation may fall short
  - adaptation may be under-financed

Challenges in Addressing Topic

- Deep scientific uncertainties about catastrophe risks
- Questions about efficacy of different strategies for mitigating CC risks
- Perception that standard rational choice methods are inadequate for assessing risks, identifying policy approaches

Outline

- Potential for Climate Catastrophes
- Decision Frameworks
- Analysis of Response Options
- Implications

Global CC Catastrophes

low probability events with large, global, irreversible impacts that dramatically reduce long-term human well-being

(probability rises with greater climate forcing)

Timely advance warning is uncertain

Types of Catastrophes

- "*Unfolding*" Catastrophes:
  - Sea level rise, ice sheet collapse
  - Major increase in natural hazard risks
  - Major ecosystem collapses (land, water)
  - Shifting ocean currents
- "*Cascading*" Catastrophes:
  - Relatively rapid succession of droughts, crop failures → widespread mitigation, conflicts
  - Remain poorly understood
- Methane feedbacks, interactions among types of catastrophes

“Unfolding” Catastrophes

- Some likely to unfold only over long time periods (many decades, centuries)
  - Even if ice sheets collapse, consequences only develop and intensify over time
- Ecosystem collapse could occur on much shorter time scales (decades)
  - Depends on unknown magnitude and speed of temperature responses, other climatic changes

"Unfolding" Catastrophes

- Physical tipping points uncertain and remain challenging to detect in advance
- Relationship of socio-economic tipping points to physical tipping points is even more uncertain
  - Depends on speed of consequences
  - Adaptation capacity

“Cascading” Catastrophes

- Cumulative effect of sequence of more localized CC-induced harms each reinforcing others
  - Series of regional crop disruptions → widespread famine, land degradation, and conflict
  - Series of localized extreme weather events → larger-scale economic disruptions, reduced remittances, refugee problems, and conflict
- Mostly speculation at this point – little has been done on such risks

Literature on Global Catastrophe Valuation – Very Limited

- Weitzman simulations; Nordhaus, Pindyck
- Growth theory models with uncertain arrival or large GDP shock – Nordhaus, Pizer, Gjerde et al
- IAM work – FUND (sea level rise and cities, change in thermohaline circulation); PAGE
- More has been done on sub-global extreme events:
  - Nordhaus, Emanuel, Mendelsohn, FEEM – hurricanes and other extreme weather events
  - Episodically incurred costs are large in absolute terms; relationship to income less clear

Outline

- Potential Climate Catastrophes
- Decision Frameworks
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- Implications

Standard Rational Choice Approaches

- Integrated economy-climate models calculate "optimal" (dynamic PV-maximizing) emissions paths
- Catastrophes represented as large, permanent drop in welfare with endogenous risk
  - Risk rises with atmospheric GHG concentration
- Approach assumes risks and impacts can be characterized quantitatively

Implications of Standard Approaches

- "Optimal" near-term abatement increases with magnitude of catastrophe risk; **but,**
- The effect generally is fairly small unless
  - catastrophe is VERY large and fairly near-term relative to discount rate used; **Or**
  - discount rate is low
- Familiar positive and normative arguments for various discounting approaches inconclusive

Challenges to Standard Approaches

- Risk vs. uncertainty vs. ignorance
  - Probabilities and even possible states of the world remain very poorly or largely unknown
- "Fat tails" versus expected utility
  - Deep uncertainty looms over standard CBA
  - Expected utility does not adequately reflect risk preferences
  - Traditional risk management analytical tools have limited effectiveness in this situation

Issues Raised by Behavioral Economics

- Risk assessments "anchored" by particular frames of reference
- Difficulty in interpreting small probabilities
- Aversion to extremes or to ambiguity

Implication is possibility of systematic assessment errors by general public

Implications for Catastrophe Risk Assessment

- Assessment "biases" by public could imply more or less, faster or slower action
  - Normal technocratic view is provide more information
- How much can further research on catastrophes do to reduce such biases?
  - Considerable uncertainty on possibility of catastrophe seems likely to persist for some time

Implications for Catastrophe Risk Assessment

- Improving knowledge remains useful; **but**,
- Sound policy decisions cannot simply be based on what revealed public preferences; **however,**
- This is **not** an argument for decision makers to abandon systematic comparison of gains and losses!
- Decision makers need to exercise their judgment as agents of the general public in evaluations
  - Political economy challenge: myopia, high personal discount rates, risk aversion

Outline

- Potential Climate Catastrophes
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Evaluation criteria

- Aim is a reasoned comparison of benefits and costs (broadly defined)
- Given deep uncertainties and several dimensions of public concerns, multiple criteria can be useful
  - Certainly does not preclude economic metrics!
  - Practical difficulties to quantify many risk characteristics in a single common metric
  - Use of several metrics can reflect complex risk attitudes
  - Given tradeoffs will be made in political give and take, evaluating multiple criteria adds information

Evaluation Criteria: Example

- Effectiveness in mitigating risk
  - Several possible ways to quantify
- Cost of implementation
- Robustness – ability to be effective even with surprises in evolution of climate change threats
- Flexibility – ability to modify response as information about risks changes

Illustrative Application

1. Drastic and rapid global emission reduction
2. Global-scale anticipatory adaptation to mitigate prospective consequences of catastrophes
3. Putting particulates into upper atmosphere (form of geo-engineering to reflect incoming radiation)

Drastic and Rapid GHG Reduction

- Effective for "unfolding" and "cascading" catastrophes
- Costs would be very high unless/until there are major technology advances for mitigation
- High need for international participation
  - More difficult the higher are the costs
- Robust to surprises in nature of risks
  - Unless (BIG) surprise is risks are low
- Inflexible – requires sustained commitment to decarbonization

Global-Scale Anticipatory Adaptation

- Purchase land for mass relocation and begin preventative relocation
- Drastically limit development in ecosystems and increase buffer areas to improve resilience
- Massive structural controls against sea-level rise

Global-Scale Anticipatory Adaptation

- Effectiveness would vary with action
  - Land acquisition for relocation could sharply limit natural hazard risks
  - Ecosystem protections would have positive impacts, but magnitude hard to judge
  - Structural barriers could be ***brittle***, not performing well for more severe impacts
  - Large-scale adaptation could be particularly effective for short-circuiting potential cascading catastrophes

Global-Scale Anticipatory Adaptation

- Costs depend on action but could be very high
  - Win-win disaster risk reduction policies, ecological systems protection
- Costlier options have little flexibility
- Portfolio of actions needed to have robustness
  - Hazards of sea level rise versus ecosystem collapse

Particulates in Upper Atmosphere

- Successful implementation would be effective and robust in blunting impacts of GHG accumulation
- Direct costs could well be less than drastic GHG mitigation, but further R&D costs could be considerable; **but,**
- Highly uncertain side effects could create very large overall costs, non-robust solutions
- Significant RD&D costs needed to establish large scale feasibility and some confidence in safety

Particulates in Upper Atmosphere

- Could use flexibly, to complement GHG abatement or responding to warning signs; **but,**
- This requires adequate capacity to detect risks of looming catastrophe in time; **and,**
- Highly inflexible once deployed
- Significant international coordination needed to deter unilateral use with strong negative spillovers

Summary of Evaluations

Evaluation Criteria	**Drastic Global GHG Reduction**	**Massive Anticipatory Adaptation**	**Particulate Injection to Upper Atmosphere**
Effectiveness	High	Medium	Potentially High
Cost	High w/o major innovation for mitigation; Low post-mitigation	Low (with high co-benefits) to High (very disruptive changes)	Potentially Very High
Robustness	High	Low (individual measures) to Medium (for portfolios)	Potentially High for dampening CC; Low for side effects
Flexibility	Low	Low	Extremely Low (absent drastic mitigation later)

Summary of Evaluations

- Certainly potential for effectiveness, robustness
- All options have high cost unless there is massive advance in low-carbon technology
  - All the more if action needed more quickly
- All options have low flexibility once implemented

Outline

- Potential Climate Catastrophes
- Decision Frameworks
- Analysis of Response Options
- Implications

Implications for Social Cost of Carbon

- Cost Benefit Analysis provides much important info needed to assess expected GHG accumulation cost
  - Need also to consider its variance, and its incidence
- Standard CBA provides considerably less help for evaluating potential impacts of catastrophes and economic value of mitigation measures
- But the principle of carefully weighing benefits and costs remains valid; instead we need to consider different approaches to this assessment
  - Problematic nature of vague "precautionary principle"

Implications for Social Cost of Carbon

- Need to consider SCC vis-à-vis catastrophe risks in terms of the willingness of public today to bear costs in an effort to mitigate such risks
  - Variety of motivations possible – but for this purpose the magnitude is the most important to understand
  - Willingness to bear costs is not fixed; strongly depends on individual values, social norms, understanding

Implications for Social Cost of Carbon

- Willingness to bear costs for reducing prospect of future catastrophes depends on many unknowns:
  - Baseline hazards, public attitudes and values
  - Innovation in GHG mitigation that lowers future cost of rapid, deep emissions cuts
  - Ability of large-scale anticipatory adaptation to lower risks from extreme events
  - Possibilities and risks associated with geo-engineering

Thought Experiment for One Approach to Catastrophe Mitigation

- Define a provisional long-term climate protection goal (X ppm, or Y° C, or…..)
- Simulate backwards a set of feasible approach paths
- Evaluate implementation costs and other attributes of different paths
  - Dependence on certain technical advances
  - Dependence on certain assumptions

Thought Experiment for One Approach to Catastrophe Mitigation

- Form expert judgments on alternatives:
  - How large would long term risk reduction benefits have to be to justify mitigation costs?
  - How could mitigation costs be reduced by less ambitious targets or more aggressive adaptation?
  - What are the types as well as sizes of residual risks?
- Put the options into the public domain for debate
  - Help public understand options and accept choices
  - Public feedback helps decision makers refine their judgments about what protection costs are acceptable

Implications for strengthening response options

- Uncertainties with all three options imply very high value of information with larger R&D funding
  - New options for drastic decarbonization
  - Stronger options for large-scale adaptation
  - More research on various types of geo-engineering to clarify their risks before they are used unilaterally
- Investigation of nature and prospects for "cascading" catastrophes is needed to evaluate their seriousness

Implications for International Assistance Measures

- Actions to reducing catastrophe risks need to be approached at strategic level
  - Carbon "shadow price" on a few fossil energy projects will have minimal impacts
  - Same with non-coordinated adaptation
- Priorities for sector – level responses need to be set (energy, food, water, coastal zones, public safety…)
- Political economy of financing-related "carrots and sticks" is very complex but needs to be addressed

Implications for International Cooperation

- Once conditions begin to deteriorate it might be easier to get international cooperation; **but,**
- Greater developing country vulnerability may cause developed countries to turn inward
- Reduction of "adaptation gap" is an urgent priority with large co-benefits

Thank you!

Comments welcome.

International Cooperation

- Experimental economics show people value fairness and cooperation giving hope that international climate agreements can be successful
- Yet consequences are asymmetrically distributed
  - Impacts vary by region
  - Different populations, among and within countries, will have highly varying ability to cope with such outcomes.
  - Poorer countries or those with closed economies are least capable of adaptation, and will have to rely on the other countries to bear the risk.
  - Migration and international trade may function to diversity risks, especially if the effects of a catastrophe are geographically concentrated.
  - Concerns about equality of outcomes affect social welfare functions
  - Even if rich countries decisions agree to bear global costs of CC, it is unclear how to square that policy decision with policies of foreign aid.

Implications for International Cooperation

- Prospects for major global actions are limited when seen as costly, with distant/uncertain payoff
- Without cooperation in risk assessment as well as implementation, benefits of careful weighing of options can be negated by others' actions

Nonmarket impacts

Michael Hanemann

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Topics

- Spatial and temporal aggregation in assessment of impacts understates impacts.
- Extreme local events account for most of non-catastrophic damages.
- Risk aversion should be accounted for.
- Impacts are multi-attribute. A univariate utility function, treating consumption as perfect substitute for environment, understates damages.

Two of the charge questions

Q: How is the value of non-market impacts currently represented in IAMs?

A: They are not meaningfully represented in current IAMs. But neither are many of the market impacts.

Q: What are the key challenges of quantifying and incorporating non-market impacts into IAMs?

A: The greatest challenge is *not* monetization. It is measurement of the physical impacts. One needs a disaggregated, bottom-up approach to the assessment of non-market impacts – and most market impacts, too.

Damages in DICE 2002

ECONOMIC IMPACT OF 2.5° C WARMING: ANNUAL DAMAGES IN THE US	
FROM NORDHAUS & BOYER (2002)	
	US TOTAL $ 1990 billions
MARKET IMPACTS	
Agriculture	4
Energy	0
Water	0
Sea Level	6
MARKET SUBTOTAL*	11
NONMARKET IMPACTS	
Health, water quality, human life	2
Human amenity, recreation, nonmarket time	-17
Ecosystem damages, species loss	0
Human settlements	6
Extreme and catastrophic events	25
NONMARKET SUBTOTAL*	17
MARKET + NONMARKET TOTAL*	28
* Totals do not add due to rounding.	

- Nordhaus & Boyer (2002) expressed as annual willingness to pay per US household (2006$)

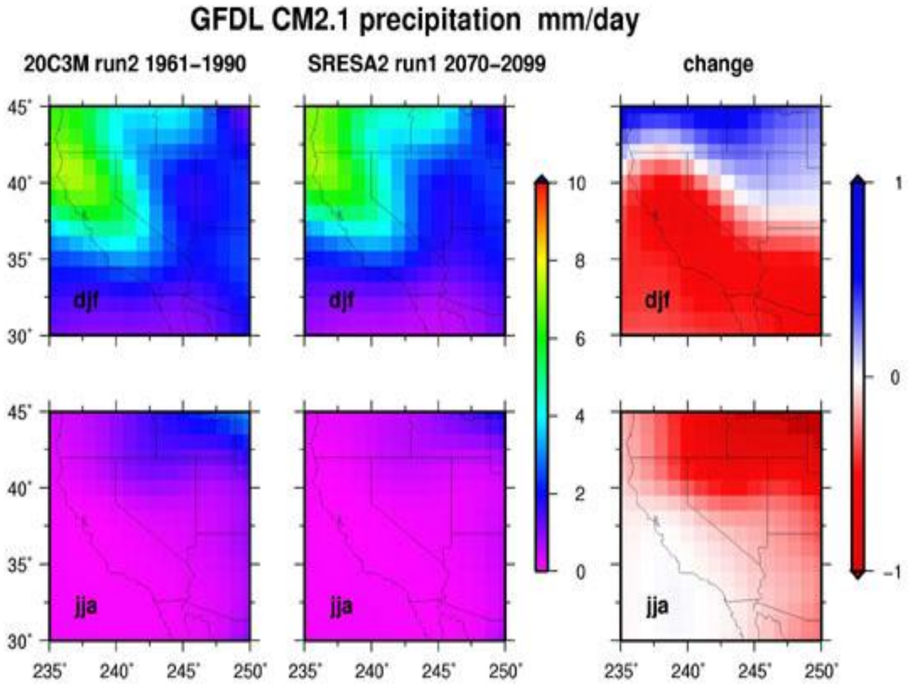
– Market impacts	$126
– Non-climate catastrophe non-market impacts	-$103
Subtotal	$ 23
– Climate catastrophe non-market impacts	$298
– Total	$321

What is missing?

- Averaging understates damages
- Neglect of extremes understates damages
- Assumption of symmetry of positive and negative impacts understates net damages
- Neglect of tail dependence understates damages
- Failure to allow for risk aversion understates damages
- Ignoring distributional considerations & loss aversion understates damages

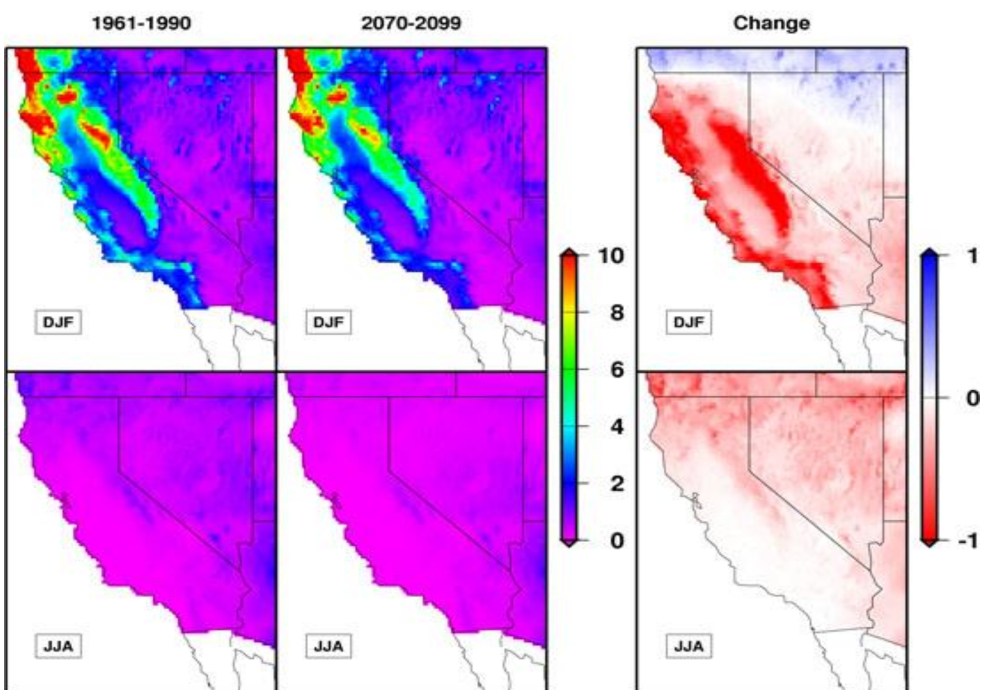
Climate impact studies

- California has been conducting impact assessments since ~2000.
- Three rounds of assessment have been completed (2002, 2006, 2009). Now on fourth round.
- Key feature of this and other recent work is spatial downscaling of GCM projections.
- Spatial downscaling has transformed impact studies in last decade.



Global Climate Models compute Climate on a coarse grid

So, a “downscaling” procedure was used to provide temperature and precipitation over a finer mesh that is more commensurate with the California landscape



A hydrologic model is used to simulate streamflow, soil moisture and other hydrologic properties

- Goal: “A more transparent representation of the pathways through which climate change may affect productivity and human well-being.”
- While mitigation is global, impacts and adaptation – both market and non-market – are *local*. They are spatially and temporally heterogeneous.
- Without adequate representation of the heterogeneity, there is neither a transparent nor an accurate characterization of impacts (damages).

Aggregation distorts conception of temperature change Hayhoe et al PNAS 2004

HOW TO CHARACTERIZE THE CHANGE IN TEMPERATURE, 2070-2099, USING HADCM3			
		EMISSION SCENARIO**	
		A1fi	B1
Change in global average annual temperature		4.1	2
Change in statewide average annual temperature in California*		5.8	3.3
Change in statewide average winter temperature in California*		4	2.3
Change in statewide average summer temperature in California*		8.3	4.6
Change in LA/Sacramento average summer temperature		~10	~5
*Change relative to 1990-1999. Units are ˚C			

- Spatial disaggregation is a major challenge for economic analysis.
  - CGE models are highly spatially aggregated.
- For given ΔT, yield effect differs by crop and location:
  - Impact on corn different than on wine grapes. Even for grapes, impact different in Napa County vs Fresno County.
  - Can’t represent impact via one “representative farm”
- Two neighboring water districts:
  - Different water rights, different sources of supply, different cost structures, different crops grown, & different climate impact.
  - Water isn’t fungible. Can’t represent a heterogeneous area via a “representative farm” with a lumped, regional supply of water, without distorting the economic analysis.

- Aggregation: Treat all days with a temperature above 90ºF as the same, as opposed to, say, 90-94, 95-99, 100-105, etc [e.g. Deschenes and Moretti (2007)]

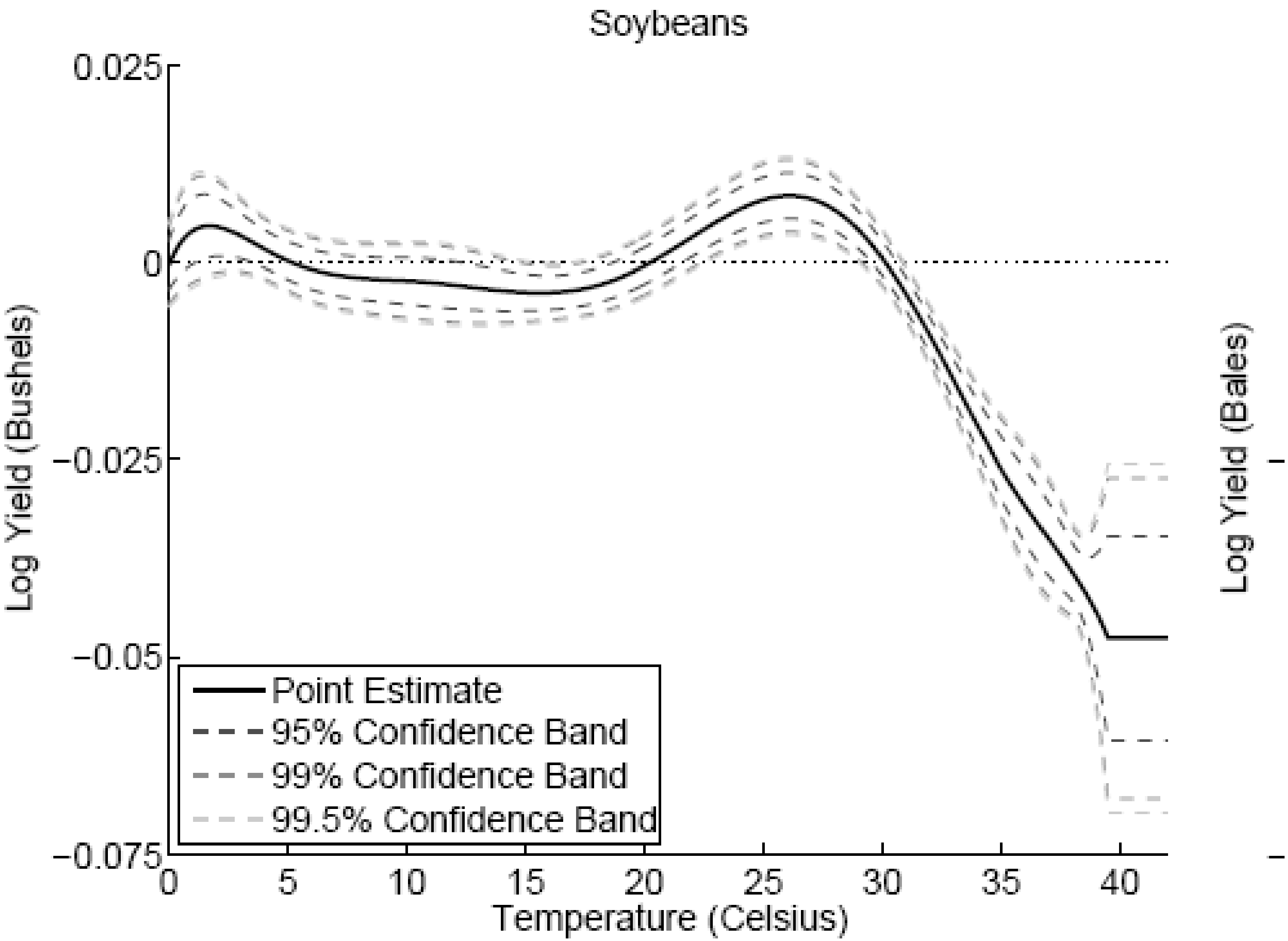
- General Consequence:
  - With convex damage function (increasing marginal damage), aggregation understates damages: $E\{D(\Delta T)\} > D(E\{\Delta T\})$.

Asymmetric negative & positive impacts

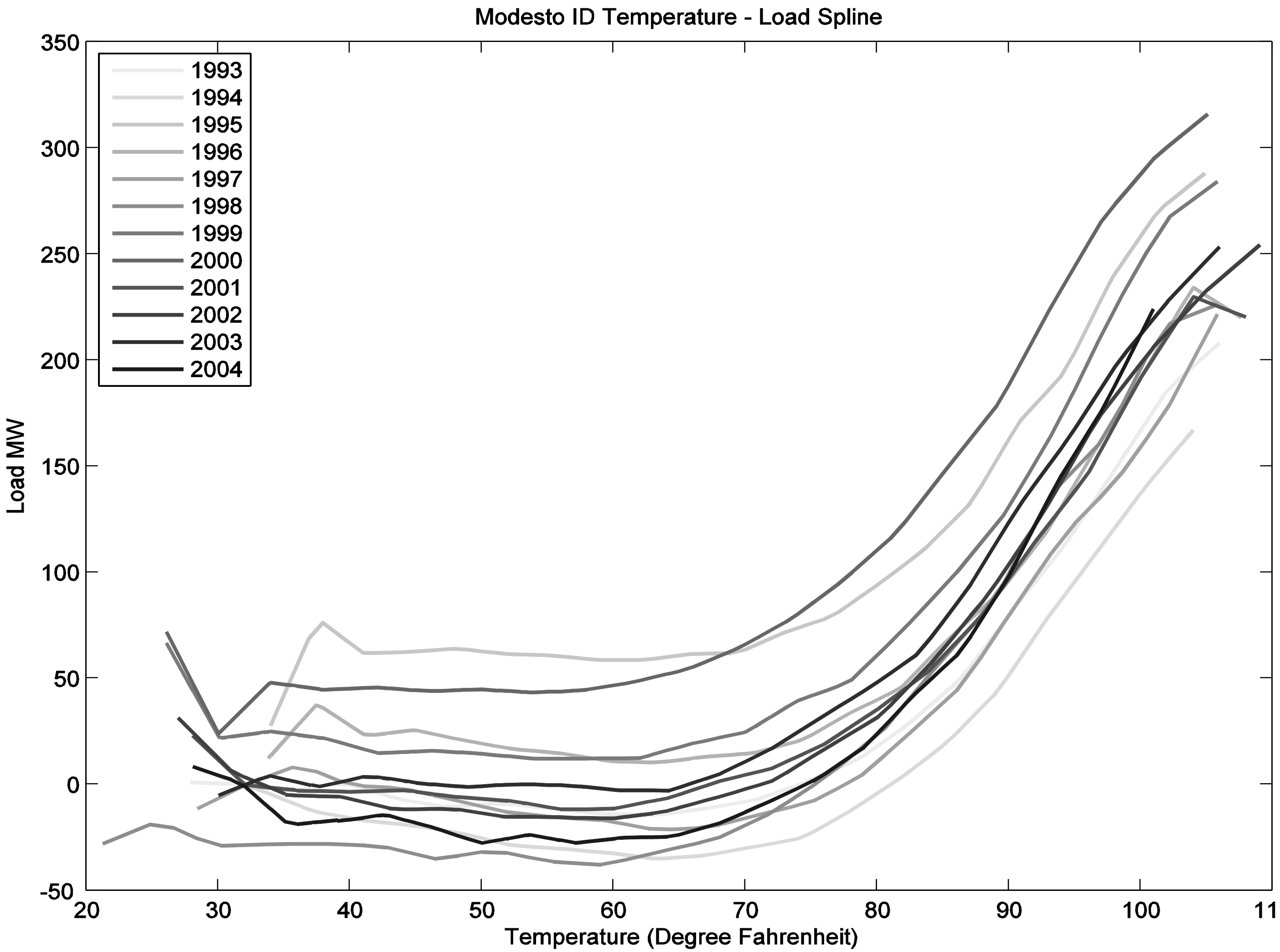
- In some cases there can be positive as well as negative impacts of climate change, depending on the degree of change.
  - Mild warming improves crop yield in cold climates, extreme warming kills crops.
  - Warming in winter reduces mortality, warming in summer raises mortality.
  - Warming in winter lowers energy bills for heating, while warming in summer raises energy bills for air conditioning.
- These effects are often represented by a quadratic, hill-shaped impact function.
- In the DICE model, Nordhaus assumes these positive and negative effects roughly cancel out.

- However, the empirical evidence suggests that the effect is generally *not* symmetric.
- Rather it is highly asymmetric
  - e.g. effect of temperature on crop yield
  - effect of temperature on energy use
- The empirical evidence suggests that, for crop yields, energy use and weather-related mortality in most countries, the negative impacts of higher temperatures greatly exceed the positive impacts of higher temperatures.

Asymmetric Relation of Temperature and Crop Yield
Schlenker & Roberts (PNAS, 2009)



Modesto Hourly Load/Temp (Aufhammer)



Nonlinear increase in flooding

- In winter storm, waves can be 5-6 ‘ higher than mean sea level. Therefore can have flood damage before sea reaches level of land.
- Scripps analysis based on an extreme wave: occurred 1 hour per year in San Francisco 1960-1980.
- By 2000, it was occurring 15-20 times per year.
- If the mean sea level at San Francisco rises by 20 cm between 2000 and 2100, expected to occur about 150-200 times per year.
- If it rises by 40 cm, an extreme hourly event would occur about 1,500 times per year.
- If it rises by 60 cm, an extreme hourly event would occur about 7,000 times per year.
- If it rises by 80 cm, an extreme hourly event would occur about 20,000 times per year.

- Most of the damages to agriculture from climate change are associated with the change in frequency of extreme events rather than the change in average temperature.
- This is probably true for many other types of impact as well.
- Weitzman has emphasized the issue of fat tails in context of updating a prior. There are also physical reasons – thresholds – why a fat tail may arise.

Modeling strategy

- The importance of disaggregation and the non-linearity of impacts has implications for the modeling strategy.
  - Need a US model as well as a global model
  - Rather than a single, integrated model, need a modular approach with a network of models
    - GCM
    - Spatial downscaling to areas within the US
    - Suite of sectoral models/analyses at loc
    - al level
    - Aggregate to national level for US
- This is more feasible if aim is to calculate SCC, rather than to determine optimal US emissions.

Implication: wrong damage function?

- The special role of extreme events affects the exponent in the damage function.
- Moreover, damages are represented as a function of the increase in temperature. But, it is likely that they are also an increasing (?convex) function of
  - The *trajectory* of increase in temperature (e.g., the increase measured in degree years).
  - The speed of increase in temperature.
- This would significantly change the economically optimal trajectory of emissions.

Reframing climate change in terms of risk

- Because the largest part of the damages from climate change is likely to be associated with extreme events, one should think of climate policy in terms of risk assessment and risk management.
- In assessing potential damages, there needs to be an allowance for risk aversion. This is largely absent in most of the existing economic literature on climate.

- The DICE model allows for risk aversion with respect to collapse of the thermohaline circulation, but not with regard to ordinary market and non-market losses.
- These are local impacts (fire, flooding, drought etc), but the local population which is exposed to them is likely to have some degree of risk aversion and some WTP to lower their exposure to these risks.
- There are limits to the extent to which these risks can be pooled
  - Non-financial outcomes (pain and suffering, etc)
  - Tail dependence
- Therefore, there should be some allowance for the public's risk aversion premium to avoid these risks.
- Moreover, the relevant risk concept is likely to be *downside* risk aversion.

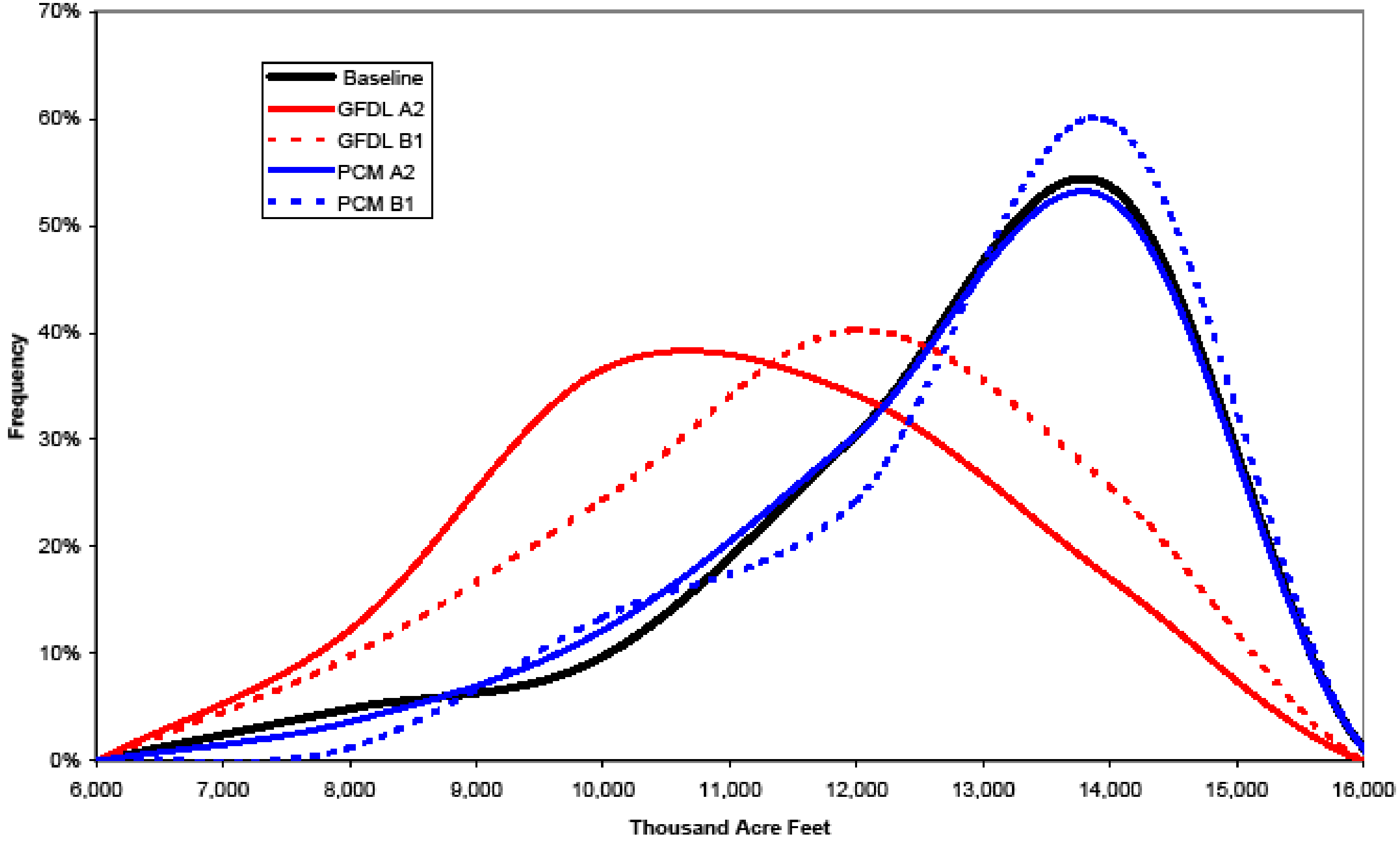
Downside risk

- This is a modification of the conventional theory of risk aversion.
- It is based on the notion that there is some asymmetry in risk attitudes towards outcomes.
- Downside outcomes (defined relative to some point) are weighed more heavily than upside outcomes.
- The concept was first applied in the financial literature in the 1970s – going broke is viewed differently than making a profit.
- It is likely to apply to many physical outcomes of climate change – e.g., asymmetry between having too little water and having too much.

Example of downside risk analysis
(Hanemann et al. 2009)

- Under the downscaled projections from the GDFL model (a medium-sensitivity GCM), but not the PCM model (a low-sensitivity GCM), there is a significant increase in downside risk with respect to water deliveries for agriculture in California’s Central Valley.
- With downside risk aversion there is a significant risk premium associated with that change.

Annual deliveries to Central Valley agriculture, 2085



Downside risk-adjusted impact

CENTRAL VALLEY AGRICULTURE ANNUAL NET REVENUE 2085 ($ million)			
	MEAN	DOWNSIDE RISK FACTOR	ADJUSTED VALUE
BASELINE	$415	$132	$283
GFDL A2	$314	$178	$136
GFDL B1	$349	$163	$186
PCM A2	$397	$130	$267
PCM B1	$413	$126	$287
	LOSS COMPARED TO BASELINE		
GFDL A2	$101	$46	$147
GFDL B1	$66	$31	$97
PCM A2	$18	-$2	$16
PCM B1	$2	-$6	-$4

For GFDL, consideration of downside risk increases the estimate of loss by about 50%.
For PCM, consideration of downside risk reduces the estimate of loss.

Multivariate utility

- Use of an aggregate consumption function treating consumption as a perfect substitute for, or a separable from, "the environment" (non-market impacts) understates damages.
  - Weitzman (2009) "Additive Damages"
  - Sterner & Persson (2008) "A Sterner View"
  - Carbone & Smith (2008) "Evaluating Policy Interventions with General Equilibrium Externalities"
  - Fisher & Krutilla (1975)

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

Ray Kopp

Senior Fellow, Resources for the Future

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

November 18 -19, 2010, Washington, D.C., Omni Shoreham Hotel

My Task

- Title
  - Implications for Design and Benefit-Cost Analysis of Emission Reduction Policies
- Charge
  - How can improved IAMs, aid in the design and evaluation of domestic emission reduction policies such as cap-and-trade or carbon taxes, and inform negotiations of international climate agreements?

Frame of Reference

- Focus my remarks on three specific classes of policymakers
  - Legislative (domestic policy design)
  - Foreign Policy (global policy design)
  - Regulatory Agency (policy implementation)
- Emphasize policymaker's needs and how those needs might be met with information from IAM's

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  - What is the benefit-cost ratio of, for example, a $25/ton carbon price?

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UNFCCC, Major Economies Forum, G20

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  - How would a global carbon market affect international trade and investment?
  - How would large-scale "green growth" policies affect trade and investment?

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- There may be roles for IAM's to play in regulatory design other than RIAs, but the role will be specific to the regulation in question.

Information Likely to be of Future Value

For Legislation and Foreign Policy

- Detail on the distribution and severity of damages (by geography, demography and economic sector)
- Characterization of adaptation potential to lower damages
- Estimate of damage sensitivity to the speed of climate change

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- Value of future climate damages is measured by the preferences of people living today
- People living today will themselves not enjoy the benefits of mitigation activity
- Why then would people living today be willing to pay anything to avoid climate damages?

# # #

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- WTP to prevent climate damages is the classic case of intra and intergenerational bequest value and altruism
- Estimates of these values are wholly absent from the SCC analysis. One wonders why

Natural Capital and Intra- Generational Equity in Climate Change

Geoffrey Heal

Columbia University[1]

1 Introduction

There are two dimensions of equity that are relevant in an evaluation of the impact of climate change – inter- and intra-generational. It is the former that has been most discussed in the literature to date – all of the extensive debate about the choice of a discount rate in climate models is in effect a debate about intergenerational equity and how to model our concerns about this. And clearly this is very relevant in a climate context – emissions made today will affect generations not yet born, so that issues of intergenerational fairness are central to any discussion of climate policy. But intragenerational issues loom large too: climate change is an external cost imposed largely by rich countries on poor ones, and in addition there is evidence that in any given country it affects poor people more than rich. This dimension of climate change has not been extensively discussed.

Climate change affects our stock of natural capital – for example, the IPCC has estimated that by 2100 in the range of 30-40% of currently extant species may be driven extinct by climate-induced changes in their ecosystems. This would represent a massive transformation of the biospehere, one unprecedented in human history. Glaciers and snowfields are also likely to diminish greatly in extent, affecting water supplies to many regions. Changes like this in our natural capital could have far-reaching consequences, and these are likely to be felt more by poor than by rich countries, and more by poor than rich groups in any country (World Bank 2006). So intra-generational equity and natural capital impacts are related: the latter is likely to reinforce concerns about the former. An important question here is whether some other form of capital – human, intellectual or physical, can replace natural capital. To the extent that this is possible, it may be possible to ameliorate some of the intra-generational equity impacts of climate change.

In the notes that follow, I begin to develop some of these points, making suggestions about how they might be modeled.

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[1] Prepared for an NSF workshop on *The Damages from Climate Change*, November 2010. Author's contact details: Columbia Business School, NY 10027, geoff.heal@gmail.com, www.gsb.columbia.edu/faculty/gheal

2 Equity and Discounting

As anyone who has spent even a short time on the economics of climate change must be aware, a central issue is the choice of the pure rate of time preference (PRTP), to be distinguished clearly from the consumption discount rate (CDR). The PRTP is the δ in the expression $\int_0^\infty u(c_t)e^{-\delta t}dt$ where c_t is aggregate consumption at time t, u is a utility function showing strictly diminishing returns to consumption and we are summing discounted utility over all remaining time.

The other discount rate concept, the CDR, is the rate of change of the present value of the marginal utility of consumption, that is, the rate of change of $\frac{e^{-\delta t}du(c_t)}{dc_t}$. For the case of a single consumption good - and we will turn to the case of multiple goods later - it follows from well-known arguments going back to Ramsey [1928] (see Heal [2005] for a review) that this is equal to the PRTP plus the rate of change of consumption times the elasticity of the marginal utility of consumption:

$$\rho_t = \delta + \eta(c_t)R(c_t) \tag{1}$$

where ρ_t is the consumption discount rate applied to consumption at time t, $\eta(c_t) = -\frac{cu''}{u'} > 0$ is the elasticity of the marginal utility of consumption and $R(c_t)$ is the rate of change of consumption at time t. (Here $u' = \frac{du(c)}{dc}$ and $u'' = \frac{d}{dc}u'$.)

What do these two discount rates mean? The PRTP δ is the rate at which we discount the welfare of future people *just because they are in the future*: it is, if you like, the rate of intergenerational discrimination. Note that there are at least two reasons why we may wish to value increments of consumption going to different people differently: one is that they live at different times, which is captured by δ, and the other is that they have different income levels, which we discuss shortly.[2] A PRTP greater than zero lets us value the utility of future people less

[2]We could also value them differently for all manner of other reasons - differences in nationality, ethnicity, and proximity either physically or genetically. In general we don't do these things, at least explicitly, which to me makes it strange that we do explicitly discriminate by proximity in time.

than that of present people, *just because they live in the future rather than the present*. They are valued differently even if they have the same incomes. Doing this is making the same kind of judgment as one would make if one valued the utility of people in Asia differently from that of people in Africa, except that we are using different dimensions of the space-time continuum as the basis for differentiation.

That an increment of consumption is less important to a rich person than to a poor person has long been a staple of utilitarian arguments for income redistribution and progressive taxation (see Sen [1973]), and is almost universally accepted. This is reflected in the diminishing marginal utility of consumption, and the rate at which marginal utility falls as consumption rises is captured by $\eta(c_t)$. Equation 1 pulls together time preference and distributional judgments, or considerations based on inter- and intra-generational judgments: the rate at which the value of an increment of consumption changes over time, the CDR ρ_t, equals the PRTP δ plus the rate at which the marginal utility of consumption is falling. This latter is the rate at which consumption is increasing over time $R(c_t)$ times the elasticity of the marginal utility of consumption $\eta(c_t)$.

3 Equity and Climate Change

As we have just seen, there are two dimensions of equity that are important in the context of climate change: equity between present and future generations, the aspect that has been most extensively discussed, and equity between rich and poor countries or groups, both now and in the future – inter- and intra-generational issues. This second dimension is invisible in aggregative one-good models, which is one reason why we need a many-good model to talk seriously about climate change. The discussions below will reinforce the need for some measure of disaggregation in the analysis of the economics of climate change if we are to grapple with equity issues.

The parameter η, the elasticity of the marginal utility of consumption, summarizes our preference for equality: it determines how fast marginal utility falls as income rises. There are two ways in which this affects the case for action on climate change.

As η rises, the marginal utility of consumption falls more rapidly. If consumption is growing over time, then this means that the marginal utility of future generations falls more rapidly with larger values of η and therefore we are less concerned about benefits or costs to future generations. We are less future-oriented - the consumption discount rate ρ is higher - and so place less value on stopping climate change. So via this mechanism, *a stronger preference for equality leads to a less aggressive position on the need for action on climate change*. Preferences for equality and action on climate change are negatively linked here.

There is another offsetting effect, not visible in an aggregative model. Climate change is an external effect imposed to a significant degree by rich countries on poor countries. The great majority of the greenhouse gases currently in the atmosphere were put there by the rich countries, and the biggest losers will be the poor countries - though the rich will certainly lose as well. Because of this, *a stronger preference for equality will make us more concerned to take action to reduce climate change*.

So we have an ambiguous impact of a stronger preference for equity on our attitude towards climate change. Via the mechanism captured in the formula for the consumption discount rate, equation 1, it makes us less future oriented - provided consumption is growing. (If consumption were to fall, it would make us more future oriented, and if consumption of some goods were to rise and that of others to fall, the effect would be a priori unclear.) And via our concern for the poor countries in the world today it makes us more future-oriented.

Unfortunately, without exception analytical models capture only the first of these effects. They are aggregative one-sector models or models with no distributive weights and so their operation does not reflect the second mechanism mentioned above. This explains the really puzzling and counter-intuitive result that a greater preference for equality in Nordhaus's DICE model leads to less concern about climate change.

To capture fully the contradictory impacts of preferences for equality on climate change policy, we need a model that is disaggregated both by consumption goods and by consumers, allowing us to study the consumption of environmental as well as non-environmental goods and also the differential impacts of climate change on rich and poor nations.

3 Natural Capital and Climate Change

Return to equation (1) for the consumption discount rate. Note that if consumption were *falling* rather than *rising* over time (the latter being the universal assumption in IAMs), then the second term in the expression for ρ_t would be negative and the CDR could in principle be negative, that is the value of an increment of consumption could be rising over time rather than falling. We would not be discounting but doing the opposite, whatever that is. It is not impossible that in a world of dramatic climate change and environmental degradation, consumption might fall at some point. It is even more likely that *some aspects of consumption, or the consumption of some social groups,* would fall while other continue to rise - recognizing this requires that we treat consumption as a vector of different goods that can be affected differently by climate change. For an early recognition of this point see Fisher and Krutilla [1975], who comment that increasing scarcity of wilderness areas may drive up our valuation of them. A more detailed analysis in the context of a growth model is in Gerlagh and van der Zwaan [2002], who make the interesting point that with limited substitutability between environmental and manufactured goods and the growing scarcity of environmental goods, there is likely to be a version of Baumol's disease - an ever larger portion of income being spent on non-manufactured goods.

Let's follow this line of thought and disaggregate consumption at date t into a vector $c_t = (c_{1,t}, c_{2,t}, \ldots c_{n,t})$ of n different goods. (We will mention briefly later the case in which thsee are the consumption levels of different countries or social groups.) Utility is increasing at a diminishing rate in all of these goods and is a concave function overall. In this case we have to change equation 1 for the consumption discount rate. Now there is a CDR for each type of consumption and we have n equations like equation 1, with a CDR for each good i equal to the PRTP plus the sum over all goods j of the elasticity of the marginal utility of consumption of good i with respect to good j times the growth rate of consumption of good j:

$$\rho_{i,t} = \delta + \eta_{ii}(c_t) R(c_{i,t}) + \sum_{j \neq i} \eta_{ij}(c_t) R(c_{j,t}) \tag{2}$$

where $\rho_{i,t}$ is the CDR on good i at date t, $R(c_{i,t})$ is the rate of change of consumption of good i at date t, and $\eta_{ij}(c_t)$ is the elasticity of the marginal utility of good i with respect to the consumption of good j (see Heal [2005] for details: the most general framework of this type can be found in Malinvaud's classic paper [1953]). The own elasticities such as $\eta_{ii}(c_t)$ are positive numbers, but the cross elasticities $\eta_{ij}(c_t)$, $j \neq i$, are zero if the utility function is additively separable and can otherwise have either sign.

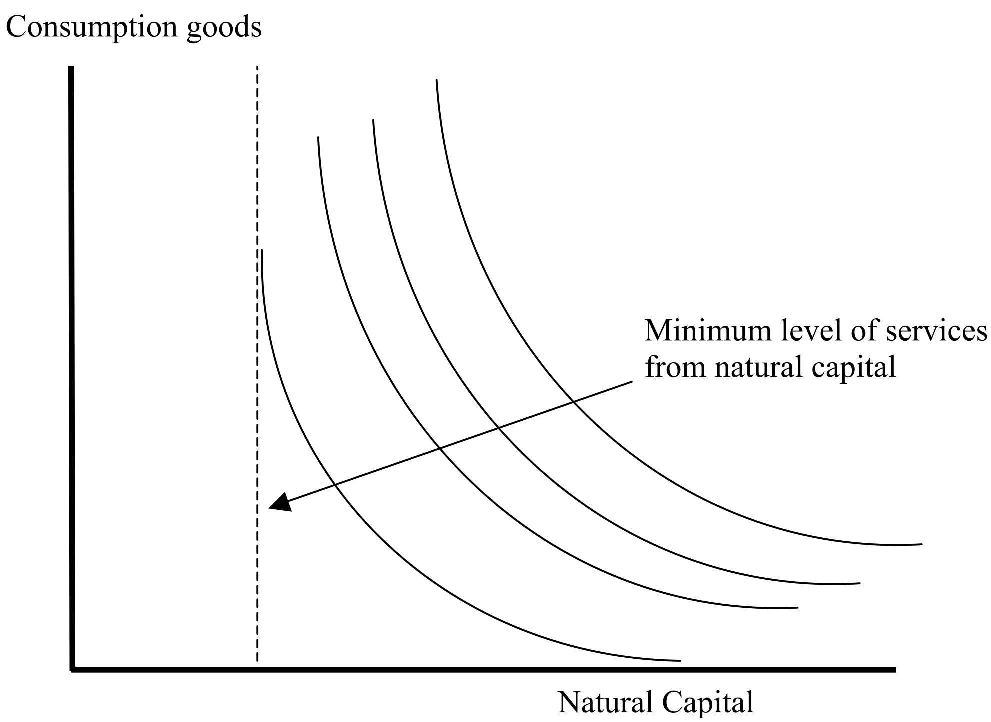
As an illustration consider the constant elasticity of substitution utility function

$$\left[\alpha c^{\sigma}+(1-\alpha)s^{\sigma}\right]^{\frac{1}{\sigma}} \tag{3}$$

Here we can think of c as produced consumption and s as natural capital, an environmental stock that produces a flow of ecosystem services. (See Barbier and Heal for a discussion of this concept [2006] and the World Bank for a detailed review of the role of natural capital in the growth process [2006].) In this case the cross elasticity of the marginal utility of consumption depends on whether c and s are substitutes or complements. For an elasticity $\sigma > 1$ they are substitutes and the cross elasticity is positive, and vice versa.

Let's test our intuitions on this. Take the case where natural capital and produced consumption are highly complementary, so that indifference curves are near to right angled and the elasticity σ is close to zero. Then the cross elasticity is negative. This means that if the stock of natural capital is rising then this reduces the consumption discount rate on the regular good. Conversely if the availability of natural capital is falling then this raises the consumption discount rate on the consumption good. These results make sense: because of the assumed complementarity, an increase in the amount of the environmental good will raise the marginal utility of the consumption good and so tend to lower the consumption discount rate, and vice versa. Of course, the own elasticity on natural capital is positive so that if the availability of this good is falling then this will tend to make its own consumption discount rate negative.

Whether produced goods and environmental services are substitutes or complements in consumption is not an issue that has been discussed in the literature, as with the few exceptions mentioned above people have worked with one-good models. There do however seem to be reasons to suppose that complementarity is the better assumption, with $\sigma < 1$. Dasgupta and Heal [1979], following Berry Heal and Salamon [1978], suggest that in production there are technological limits to the possibility of substituting produced goods for natural resources. In particular we invoke the second law of thermodynamics (Berry and Salamon are thermodynamicists) to suggest that if energy is one of the inputs to a production process, then there is a lower bound to the isoquants on the energy axis. Similarly one can argue that certain ecosystem services or products, such as water and food, are essential to survival and cannot be replaced by produced goods. There are therefore lower bounds to indifference curves along these axes, implying if the utility function is CES that $\sigma < 1$.



The figure illustrates this idea: it shows indifference curves for a two-argument utility function, consumption of produced goods and of ecosystem services, as in equation 3 above. There is a minimum level of ecosystem services needed for survival - think of this as water, air, and basic foodstuffs, all of which are ultimately produced from natural capital. For low welfare levels there is no substitutability between these and produced goods, so that indifference curves are close to right angled. At higher welfare levels where there are abundant amounts of both goods there is more scope for substitution. Taken literally, this implies that the elasticity of substitution is not constant but depends on and increases with welfare levels. This of course is not reflected in the CES function such as 3. A function with these properties is

$$\left[\alpha c^{\sigma}+(1-\alpha)(s-\varepsilon)^{\sigma}\right]^{\frac{1}{\sigma}} \quad (4)$$

which is simply the CES function we noted before, with the zero of the ecosystem service axis transformed by $\varepsilon > 0.$ Utility is not defined for $s < \varepsilon.$ Relative to the transformed origin $(\varepsilon, 0)$ there is still a constant elasticity of substitution σ but relative to $(0,0)$ the elasticity is not constant. For $\sigma > 1,$ every indifference curve, every welfare level, can be attained with only ε of ecosystem services, whereas with $\sigma < 1$ greater welfare levels require greater levels of ecosystem services (and of consumption goods).

These ideas can be applied to modeling equity: it is generally recognized that poor countries, or poor groups within countries, are more dependent on natural capital and its services than are richer groups (World Bank [2006]). They have less capacity to substitute alternative goods for the services of natural capital and so show more complementarity between natural capital and other goods. In terms of the figure, their indifference curves are lower and closer to being right angled. This means that they have different consumption discount rates from other groups: if the stock of natural capital is falling then they will have higher consumption discount rates on the common consumption good. In this sense they will appear to be more impatient. Of course as noted above their discount rate on natural capital will be negative, so we will have the paradox of an apparently impatient group – with respect to the consumption good – being willing to invest for low returns in natural capital.

4 A Sterner Perspective

It's worth looking in more detail at the Sterner and Persson development of this point [2007]. They talk about the effect of changes in relative prices rather than consumption of produced and environmental goods, but the point is the same. If we consume both produced goods and the services of the environment, as in the utility function 3, then we can expect that with climate change environmental services will become scarce relative to produced goods and therefore their price will rise relative to that of produced goods (the " environmental Baumol disease" that Gerlagh and van der Zwaan refer to [2002]). Consequently the present value of an increment of environmental services may be rising over time, and the consumption discount rate on environmental services may thus be negative, precisely the point that we were making in equation 2 above. This could be the case even with a high PRTP, which is the main point of the Sterner and Persson paper. They also present an interesting modification of Nordhaus's DICE model to incorporate this point. They replace the standard utility function, which is an isoelastic function of aggregate consumption, by a CES function along the lines of equation 3 above, but modified to reflect a constant relative risk aversion:

$$\left[(1-\gamma)c^{1-1/\sigma}+\gamma s^{1-1/\sigma}\right]^{(1-\alpha)\sigma/(1-\sigma)}/(1-\alpha)$$

They assume that the supply of environmental services s is negatively affected by temperature according to the square of temperature, and that the share of environmental goods in consumption is about 20%, use these assumptions to calibrate the modified DICE model and and then run the model with the PRTP used by Nordhaus. Their runs show that even with such a high PRTP the presence of an environmental stock that is damaged by higher temperatures radically transforms the optimal emissions path of CO_2 and leads to a vastly more conservative policy towards climate change, with emissions both staying lower and falling faster. In fact it leads to a more aggressive reduction in greenhouse gases than recommended by the Stern Review.

5 Natural Capital and Production

I have emphasized so far that natural capital can affect human welfare directly, and needs to be thought of as an argument of the welfare function. Natural capital also affects a nation's production possibilities: I mentioned above changes in hydrology such as melting of glaciers and reduction in winter snowfields, both of which are already in evidence and are affecting agriculture in some regions. They will affect it further over the coming decades. This is quite separate from any impact that changes in temperature and precipitation may have on agriculture. Other changes in natural capital will probably affect agriculture – changes in species abundance and distribution, for example, can affect whether birds and insects pollinate crops.

6 Modeling Different Groups

I commented above that equation 2 can be given a different interpretation: instead of

$$\rho_{i,t} = \delta + \eta_{ii}(c_t) R(c_{i,t}) + \sum_{j \neq i} \eta_{ij}(c_t) R(c_{j,t}) \qquad (2)$$

the subscripts i and j referring to different goods, they can be taken as referring to the amounts of a single good consumed by different groups – these could be social groups within a country or they could be different countries. I this case we hae different consumption discount rates for each group's consumption, and the elasticities now indicate how the marginal valuation of consumption by one group depends on the cosumption levels of others. Do we value on increment of consumption to the poor more if everyone else is very rich than if most others are also poor? Presumably the answer to this is yes, but these are issues that have not featured at all in the discussions to date.

7 Choosing η

The elasticity of the marginal utility of consumption plays a central role in much of outr discussion. Unfortunately this variable plays two roles in our models: it expresses our distributional preferences, which is the way we have been using it here, and it also expresses our aversion to risk. Most empirical estimates of the value of η come from studies of behavior in the face of risk, but it seems clear that these two interpretations of η are really quite different, and that our aversion to risk tells us little if anything about our preferences for income equality. Given this, we need to find a way of expressing preferences that does not conflate distributional and risk preferences. Recursive formulations such as that of Kreps and Porteus are relevant here.

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Natural Capital, Equity and Climate Change

Geoffrey Heal
Columbia Business School

Equity

- Two dimensions
  - Inter- and Intra-Generational
- Inter-generational equity bound up with pure rate of time preference delta
- Both affected by elasticity of MU, eta
- We express equity judgments of both types when we choose delta and eta

Equity

- Famous Ramsey equation for consumption discount rate ties together both:

$$\rho_t = \delta + \eta(c_t)R(c_t)$$

- CDR depends on intergenerational equity values via delta and intragenerational via eta

Equity

- As eta rises, MU of cons'n falls faster. If cons'n grows then MU of future generations falls more rapidly
- Less concerned about benefits to future.
- Consumption discount rate is higher – place less value on stopping climate change. So *a stronger preference for equality leads to less action on climate change*.

Equity

- Offsetting effect, not visible in aggregative model
- Climate change an external effect imposed by rich countries on poor.
  - greenhouse gases currently in atmosphere were put there by the rich countries,
  - and the biggest losers will be the poor countries
- Because of this, *a stronger preference for equality will make us more concerned to take action on climate change*.

Natural Capital

- Affects well-being in many ways, depending on stage of development
- Poor countries heavily dependent on services of natural capital
- Natural capital compromised by climate change

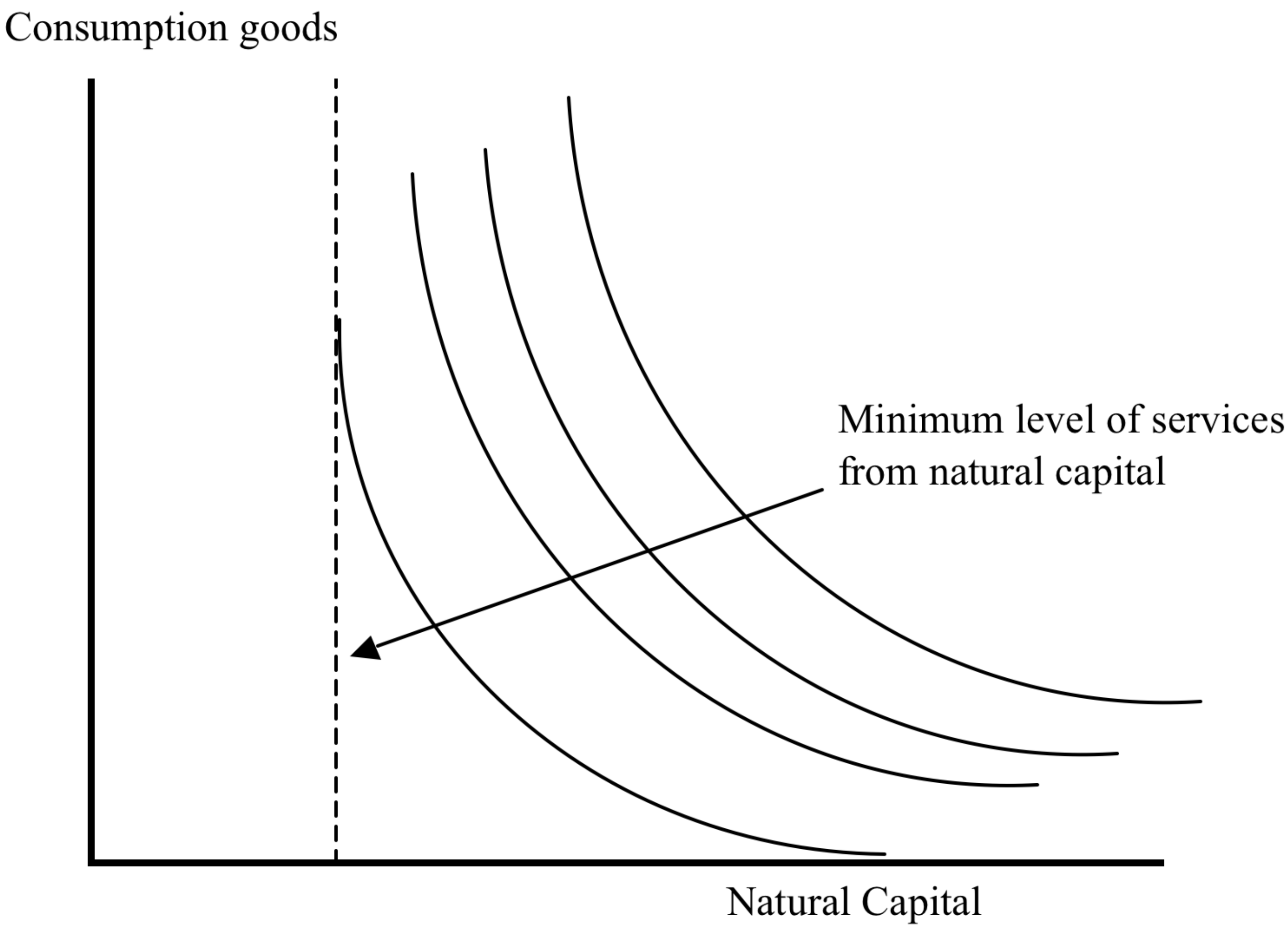
Natural Capital

$$c_t = \left(c_{1,t}, c_{2,t}, \ldots c_{n,t}\right)$$

- Ramsey equation is now

$$\rho_{i,t} = \delta + \eta_{ii}(c_t)R\left(c_{i,t}\right) + \sum_{j \neq i} \eta_{ij}(c_t)R\left(c_{j,t}\right)$$

- CDR is good-specific and can be + or -



$$\left[\alpha c^{\sigma}+(1-\alpha)(s-\varepsilon)^{\sigma}\right]^{\frac{1}{\sigma}}$$

Natural Capital

- For $\sigma > 1,$ every indifference curve, every welfare level, can be attained with only ε of ecosystem services, whereas with $\sigma < 1$ greater welfare levels require greater levels of ecosystem services (and of consumption goods).

Sterner and Persson

$$\left[(1-\gamma)c^{1-1/\sigma}+\gamma s^{1-1/\sigma}\right]^{(1-\alpha)\sigma/(1-\sigma)}/(1-\alpha)$$

- Run DICE with this objective – makes a huge difference to the outcomes

Intra-generational Equity

$$\rho_{i,t} = \delta + \eta_{ii}(c_t)R(c_{i,t}) + \sum_{j \neq i} \eta_{ij}(c_t)R(c_{j,t})$$

- Can take subscripts here to be social groups not goods

Role of Eta

- Plays several roles
  - Affects intergenerational choices via Ramsey equn, with larger value making for less concern for CC
  - Affects intragenerational choices directly, with larger values making for more concern for CC
  - Affects risk aversion
- Really need to find a formulation that separates these roles

Disaggregation

- Need models that distinguish environmental services from manufactured goods, and
- Need models that distinguish rich groups from poor
- Two dimensions of disaggregation

Implications for choice of policy targets for cost-effectiveness analysis

Nat Keohane
Chief Economist

EPA-DOE Climate Damages Workshop
November 19, 2010

EDF ENVIRONMENTAL DEFENSE FUND
Finding the ways that work

Agenda

1. The SCC is not a cost-effectiveness measure
2. What would a c/e approach look like?
3. What should we do with the SCC we have?
   - Uses and abuses of the SCC
   - Extramural uses of the SCC
4. The economics-science disconnect
5. Where do we go from here?

1. The SCC is not a cost-effectiveness measure (1/2)

Importance of precision

- “Social cost of carbon” is not a generic term

  Specific meaning: present value of the marginal damage from emitting an additional ton of GHG

- SCC doesn’t incorporate the cost of achieving a goal (→ defn of cost-effectiveness)

1. The SCC is not a cost-effectiveness measure (2/2)

So what is meant by "cost-effectiveness" here?

1. Contrast with optimal control approach
   - SCC computed along BAU trajectory
2. "Letter" vs. "spirit" of cost-effectiveness
   - Use in establishing consistency
   - Derivation vs. application

Consider derivation first, then application.

2. What would a cost-effectiveness approach look like? Key issues (1/4)

Considerations for cost-effectiveness analysis:

- What target to use? (“Effectiveness” at what?)
- What other countries do matters.
- Cost estimates aren’t perfect either.

2. What would a cost-effectiveness approach look like? The UK approach (2/4)

UK uses a cost-based shadow price measure

UK experience is instructive:

- National policy target in place
- Participation in the EU ETS cap and trade program
  - Creates a policy need for a c/e approach (trading and nontrading sectors)
  - Observable signal of marginal cost (thus not entirely model-dependent)

2. What would a cost-effectiveness approach look like? Some concrete ideas (3/4)

Some concrete ideas:

- Cost-based
  - Shadow prices to achieve a “standard set” of global scenarios (e.g., 450/550/650)
  - … to achieve a range of national targets (17%?)
- Risk-based
  - Risk management framework (defer to Roger)
  - Directly value the shift in the distribution [*]

2. What would a cost-effectiveness approach look like? Conclusions (4/4)

Common thread: Marginal analysis

These are not mutually exclusive, either with each other or with a damages-based SCC approach!

Some number better than no number, but several numbers may be better than "some number" (depending on use)

Premise of rest of talk: damages-based SCC has a role, but what should it be?

3. What should we do with the SCC we have?

Uses and abuses of the SCC (1/3)

Abuses

- As a measure of policy stringency
- As the sole input into regulatory impact analyses

Uses

- To ensure consistency across regulatory agencies ("c/e in spirit")
- As one input into regulatory impact analyses

3. What should we do with the SCC we have?

Extramural uses of the SCC (2/3)

Interagency Working Group SCC has been used in other unrelated proceedings:

- Colorado PUC proceedings
- DC Court of Appeals cases re: EPA GHG regulations
- Cape Wind

3. What should we do with the SCC we have?

Extramural uses of the SCC (3/3)

Lessons from the "extramural" uses:

- Numbers have a life of their own
- SCC provides a valuable and concrete benchmark for uses outside federal rulemaking
- Establishes the principle that marginal damages are real and can be quantified
- $21/ton >> $0/ton

What are the lessons (e.g., conveying uncertainty)?

4. The economics-science disconnect

Ex post approach

"This value of the SCC doesn't match the science"

Ex ante approach

"This input [parameter value, assumption] doesn't match the science"

Advantages:

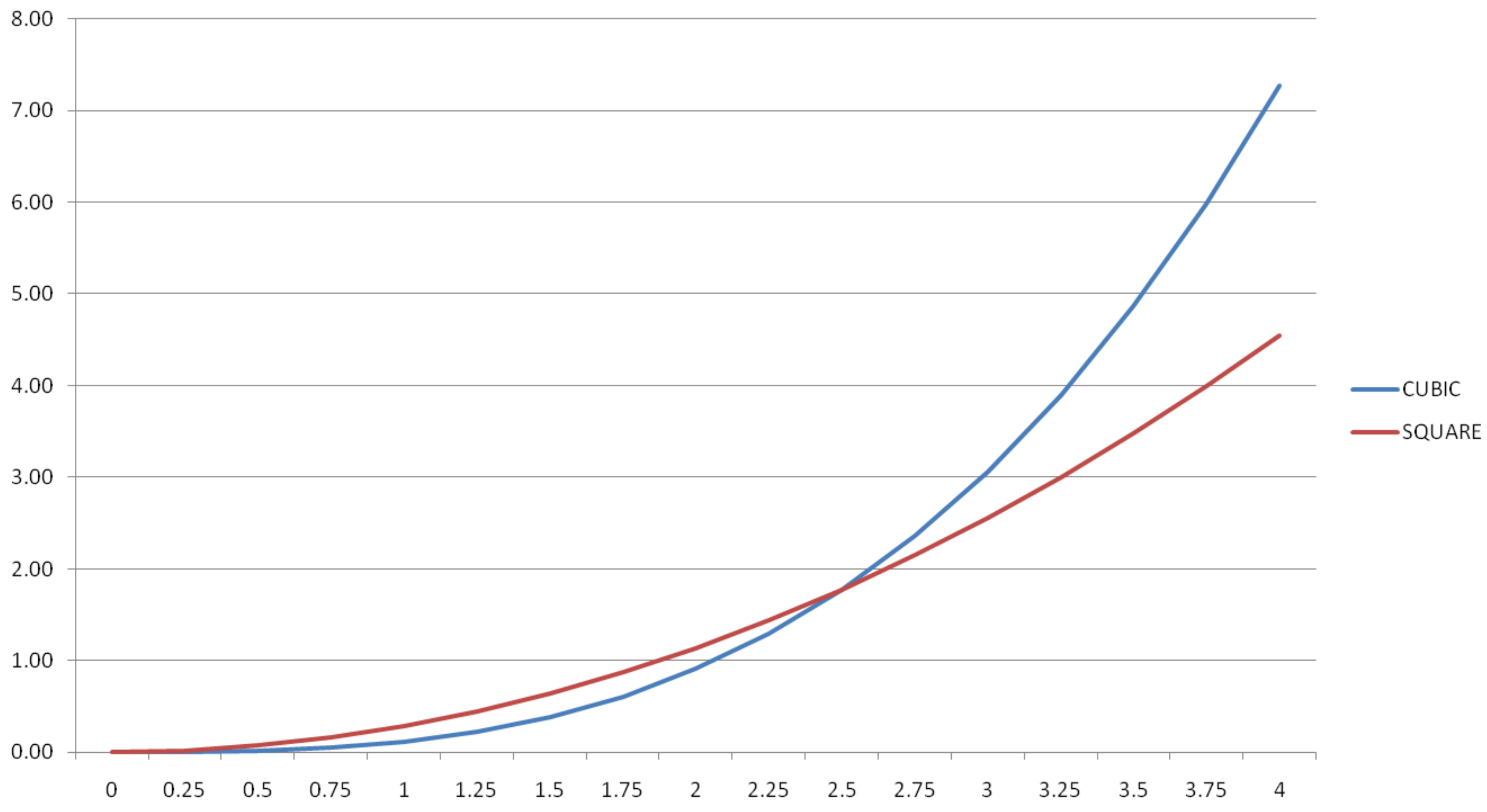
- analytic rigor
- strong foundation

Requires something of both economists and scientists.

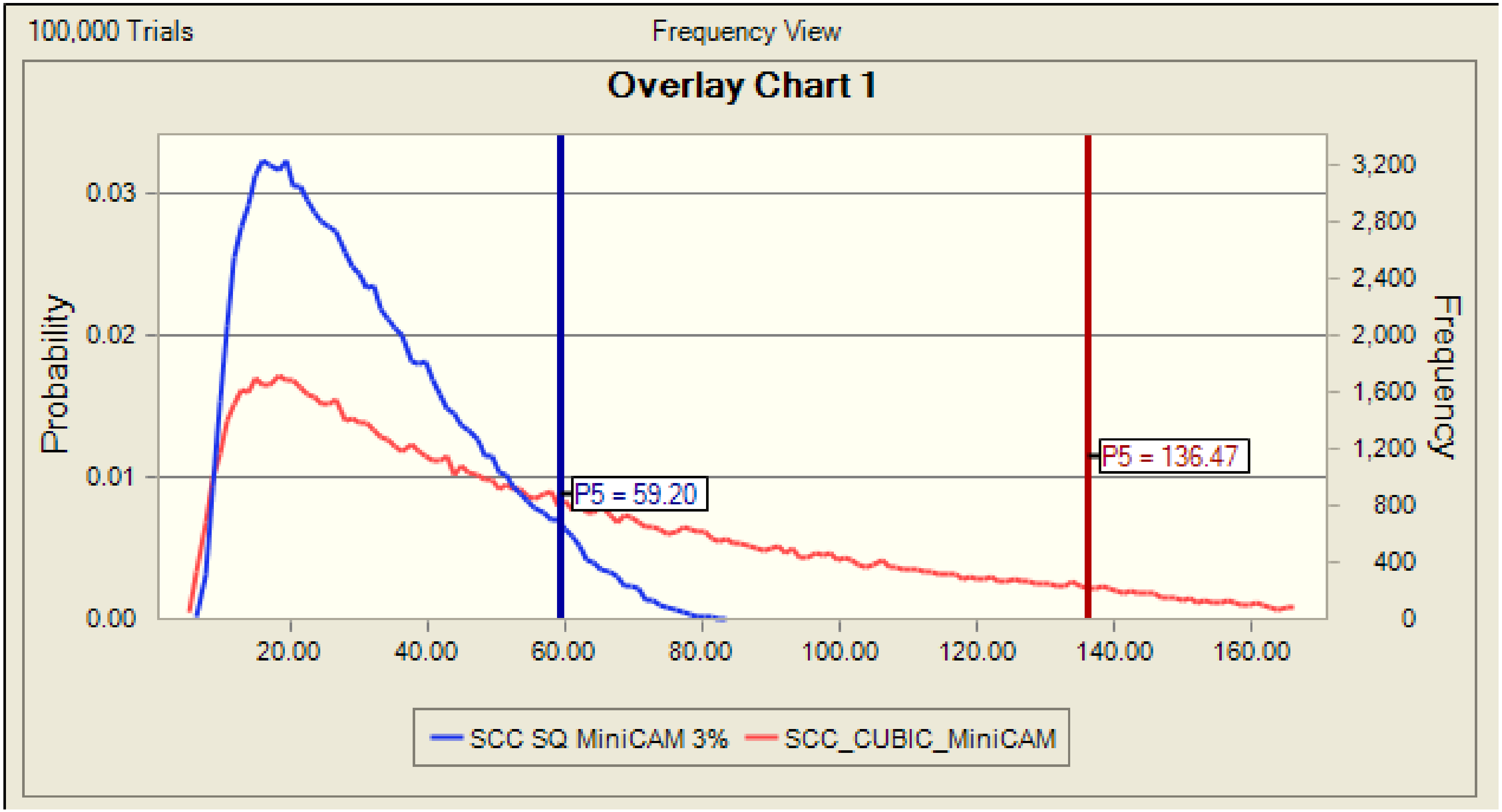
5. Where do we go from here?

- How will the results of this workshop be incorporated into a process going forward?

An aside: Which damage function? (1/2)



An aside: Which damage function? (2/2)



(Mean, Median, 95th %ile): ($30,28,59) ($56,46,136)

Abstract

Managing Climate Risks

Roger M. Cooke[1]
Carolyn Kousky[2]

Many Integrated Assessment Models (IAMs) maximize the present value of consumption, equating the marginal benefits of abatement in terms of reduced climate damages with the marginal costs of reducing emissions. Every trader, banker, and investor knows that maximizing expected gain entails a trade-off with risk. According to the theory of rational decision, preferences can always be represented as expected utility, hence from this viewpoint, any aversion to risk could be folded into the rational agent's utility function. This theory, recall, applies to rational *individuals*; groups of rational individuals do not comply the axioms of rational decision theory. The fact is that 'professional risk taking organizations' do manage risk, and not by bending the utility function of a representative consumer. Rather, they employ techniques like value at risk, and optimize expected gain under a risk constraint. Managing risk is a problem of group decision.

Weitzman (2009) has recently called attention to the risks of climate change, arguing that current approaches court probabilities on the order of 0.05~0.01 of consequences that would render life as we know it on the planet impossible. What is the plan to manage this "tail risk"? Risk management shifts the research question from 'how does the optimal abatement level change for different parameter values?' to 'how does our policy choice fare under the range of potential future conditions and how can we buy down the risk of catastrophic outcomes?' As such, it places the quantification of uncertainty in the foreground. Uncertainty quantification is more than a modeler putting distributions on his/her model's parameters. The antecedent question reads: 'is it the right model? What is the model uncertainty?' Failing a definitive answer to that question, *stress testing* our current models for their ability to handle tail risks, and exploring *canonical model variations* are essential steps prior to quantifying uncertainty on parameters. Gone are the days when quantification of the uncertainties was left to the modelers themselves; at the state of the art, quantification is done by *structured expert judgment* in a rigorous and transparent manner.

Stress Testing

Stress testing is preformed to check that models remain realistic and capture the relevant possibilities when their parameters are given extreme values. Many IAMs specify economic damages as a function of temperature change, and model their impact on output and utility. For example, damages at time t induced by temperature change T(t) from pre-industrial mean temperature are represented in DICE as factor that reduces economic output: $1/[1 + 0.0028388T(t)^2]$. The standard Cobb Douglas production function expresses output as a function of total factor productivity, capital stock and labor. Capital depreciates at rate 10%, and is augmented by savings (in the DICE "Base" case the savings rate is optimized with damages set equal to zero, then damages are reinstated). Temperature induced damages and abatement efforts reduce output. Setting damage and abatement equal to zero, an illustrative stress test of the Cobb Douglass model with constant population, constant total factor productivity and DICE values for

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other parameters is shown in Figure 1. Four output trajectories with initial capital ranging from 10 times the DICE value ($1800 Trill) to $100 ($$1.6\times10^{-8}$ for each inhabitant). The limiting capital value is independent of the starting values – with a vengeance: the four trajectories are effectively identical after 60 years. Such obviously unrealistic consequences underscore the need for circumscribing the empirical domain of application of these simple models. Put the factories and laborers on the Moon and they will produce nothing; other things are involved. Regardless whether the model adequately describes small departures from an equilibrium state, its use for long term projections inevitably entails this sort of behavior and putting uncertainty distributions on the model's parameters will not change that.

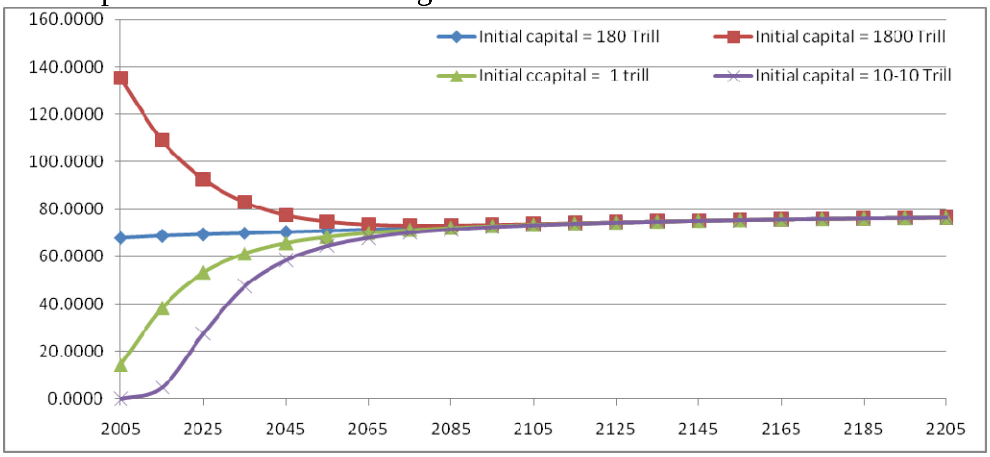


Figure 1. Output gross of abatement cost and climate damage ($trill 2000 USD) Base case, no temperature damage, no abatement, constant population, constant total factor productivity (0.0307951), initial output from production function and DICE defaults for other parameters (DICE 2009 XL version).

A second stress test examines the effect of adding temperature induced economic damages, again without abatement. With $180 Trill initial capital, we assume that temperature increases linearly, leaving other parameters as in the previous case. Figure 2 shows four economic output trajectories, corresponding to temperature increases of 0, 5, 10, and 15 degrees Celsius in 200 years.

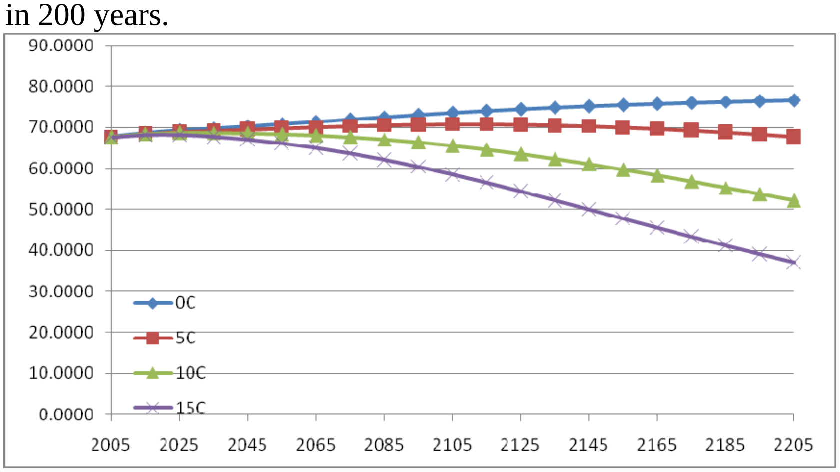


Figure 2Output after damages before abatement, initial capital = 180 $trill, constant population, constant productivity, no abatement, temperature in 200 yr (linear increments)

No scientist claims that life as we know it could exist with 10°C global warming. With a steady temperature rise leading to 10°C above pre-industrial levels in 200 years, this model predicts that output would be reduced to 68.% of its value without temperature rise. Such projections seem a bit sanguine. The essential feature is that climate induced damages hit only economic output; as a result capital can never decrease faster than its natural depreciation rate, and this rate of decrement is reached only for infinite temperature. Again, putting uncertainty on other model parameters may cloud this picture, but will not change this feature.

Canonical Model Variation

It is often noted that simple models like the above cannot explain large differences across time and geography between different economies, pointing to the fact that economic output depends on many factors not present in such simple models. To "save the phenomena" researchers have proposed enhancing the basic model with inter alia social infrastructure, government spending, human capital, knowledge accretion, predation and protection, extortion and expropriation (see Romer (2006), chapter 3). Before proliferating this model, however, it is well to reflect on its fundamental assumptions about damage, capital and output. Could different model types with comparable prime facie plausibility result in macroscopically different behavior?

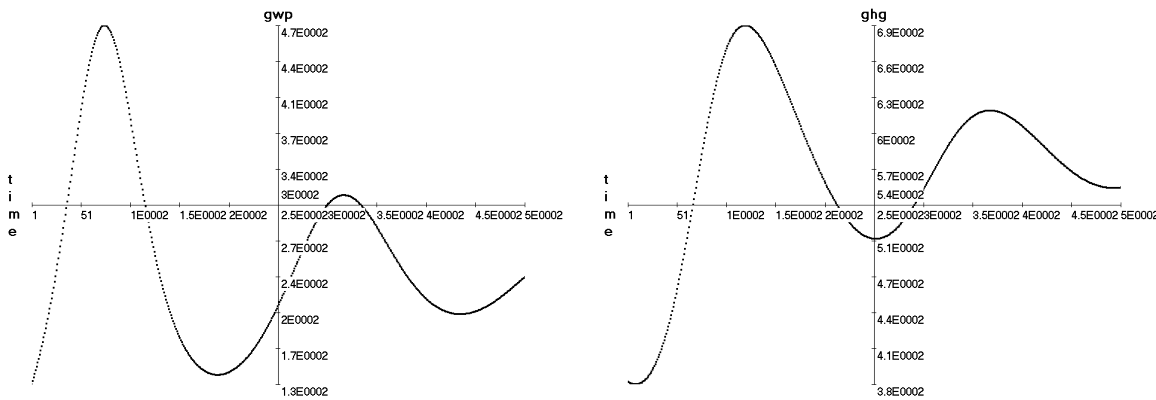
We illustrate with one variation based on the following simple idea: Gross World Production (GWP[trillion USD 2005]) produces pollution in the form of greenhouse gases; pollution, if unchecked, will ultimately destroy necessary conditions for production. This simple observation suggests that Lotka Volterra type models might provide a perspective which an uncertainty analysis ought not rule out. The quantity of anthropogenic greenhouse gases in the atmosphere at year t, GHG(t) [ppm CO_2], is the amount in the previous year, less what has decayed at a rate, say, 0.0083, plus any new emissions in time period t. Assume that new emissions are a fixed fraction, say, 0.024 of GWP (Kelly and Kohlstadt 2001). Different values can be found in the literature, but these are representative. Real GWP has grown at an annual rate of 3% over the last 48 years (this includes population growth); assume that this growth is decreased by a damage function D of temperature T, and ultimately of GHG, this gives the following system:

(1) $\quad GHG(t+1) = (1-0.0083)GHG(t) + 0.024\times GWP(t).$

(2) $\quad GWP(t+1) = [1+ 0.03 - D(T(GHG(t)))]GWP(t).$

If D were linear in GHG, this would be a simple Lotka Volterra type system. With *cs* as the climate sensitivity and 280 ppm the pre-industrial level of greenhouse gases, equilibrium temperature follows $T(GHG(t)) = cs\times \ln(GHG(t)/280)/\ln(2)$. Adopting Weitzman's (2010) notion of a "death temperature" of 18°C we write damages as $D(GHG)(t) = (T/18)^2$. Anthropogenic greenhouse gases increase with production; if GWP(t) were constant, they would increase to a constant 0.024×GWP/0.0083 However, as GWP increases, GHGs and temperature keep rising as well, lowering the growth rate of GWP. When $D > 0.03$, GWP starts decreasing. Eventually $0.024\times GWP < 0.0083$, and then greenhouse gases start decreasing, reducing damages to a point where production can start growing again. Figure 2 shows GWP and GHG as functions of time out to 500 yrs, with all variables at their nominal values. GWP collapses. Greenhouse gases also collapse, but not to their initial level; hence the next upswing in GWP is attenuated. A steady state is eventually reached after some 1,500 years. This is not offered as a plausible model, its role is to spotlight the fundamental modeling assumptions. Evidently, different ways of modeling the impact of climate change damages give qualitatively different predictions, and steady state values may not be relevant for current policy choices. Neither theoretical nor empirical evidence exclude the Lotka Volterra type of interaction between damages and production presented here. A credible uncertainty analysis should fold in this and other possibilities, which brings us to the next point of examining a range of future conditions for a given policy choice.

Figure 3: The impact of climate damages on GWP (left) and greenhouse gases (right)

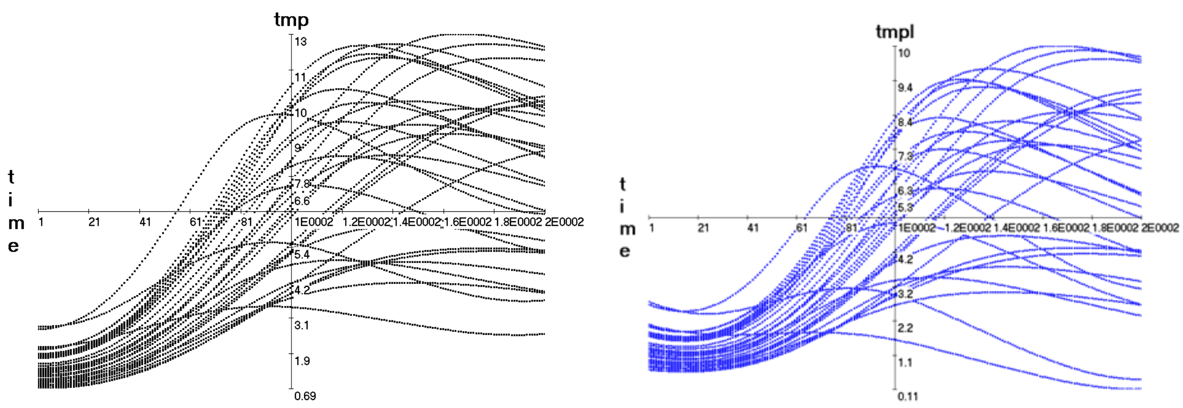


Structured Expert Judgment for Quantifying Uncertainties

Uncertainty analysis with climate models must be informed by the broad community of climate experts - not simply the intuitions or proclivities of modelers - through a process of structured expert judgment. Experience teaches that independent experts will not necessarily buy into the models whose parameter uncertainties they are asked to quantify. Hence, experts must be queried about observable phenomena, results of thought-experiments if you will, and their uncertainty over these phenomena must be 'pulled back' onto the parameters of the model in question. This process is analogous to the process by which model parameters would be estimated from data, if there were data. The new wrinkle is that data are replaced by experts' uncertainty distributions on the results of possible, but not actual, measurements. The 'pull back' process is called probabilistic inversion, and has been developed and applied extensively in uncertainty analysis over the last two decades (see Cooke and Kelly 2010 and references therein). In general, an exact probabilistic inverse does not exist, and the degree to which a model enables a good approximation to the original distributions on observables forms an important aspect of model evaluation. Four features of the structured expert judgment approach deserve mention: (i) Experts are regarded as statistical hypotheses, and their statistical likelihood and informativeness are assessed by their performance on calibration questions from their field whose true values are known post hoc. (ii) Experts' ability to give statistically accurate and informative assessments is found to vary considerably. (iii) Experts' uncertainty assessments are combined using performance based weights. (iv) Dependence, either assessed directly by experts or induced by the probabilistic inversion operation, is a significant feature of an uncertainty analysis.

When uncertainty has been quantified in a traceable and defensible manner, an ensemble of possible futures for each policy choice may be generated. Figure 4 shows 30 Lotka Volterra temperature trajectories out to 200 years, with BAU emissions at 2.4% GWP (left) and stringent emissions at 1.5% of GWP (right); and using representative distributions for uncertain variables. Employing a value at risk management strategy, we would search for an emissions path optimizing consumption while holding the probability of exceeding a stipulated temperature threshold below a tolerable threshold.

Figure 4: Possible temperature trajectories under (left) emissions at 2.4%GWP and (right) emissions at 1.8% GWP (right)



These reflections challenge us to deploy risk management strategies on a global scale. We suggest this begin with (i) stress testing models, (ii) exploring alternative models, and (iii) quantifying uncertainty in such models via structured expert judgment. We are condemned to choose a climate policy without knowing all the relevant parameters, but we are not condemned to ignore the downside risks of our choices.

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Managing Climate Risks

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18-11-10

Key Points

- Why Risk Management?
- Total Uncertainty = Model + Parameter
- Climate Damage: Inner and Outer Measure

Rational Decision Theory

- A rational agent maximizes expected utility
- (subjective) probability and utility unique *to individual*
- Climate change is a group decision problem
- Professional risk takers don't manage risk by bending the utility function of a 'representative consumer'
- Probabilistic Design: optimize performance under risk constraint

Risk Management Approach

★ Risk-averse representative consumer

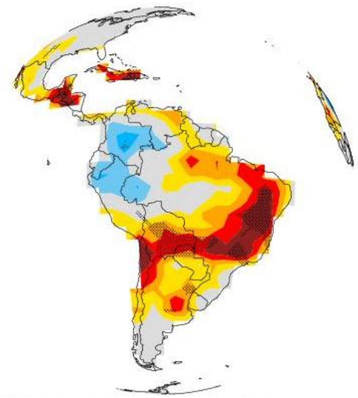
- **Discounting**
- **Utility function**
- **Utility of civilization**

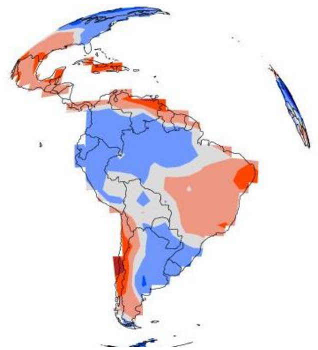
And / Or

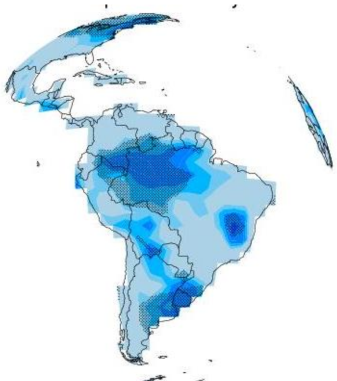
★ Risk-constrained optimization

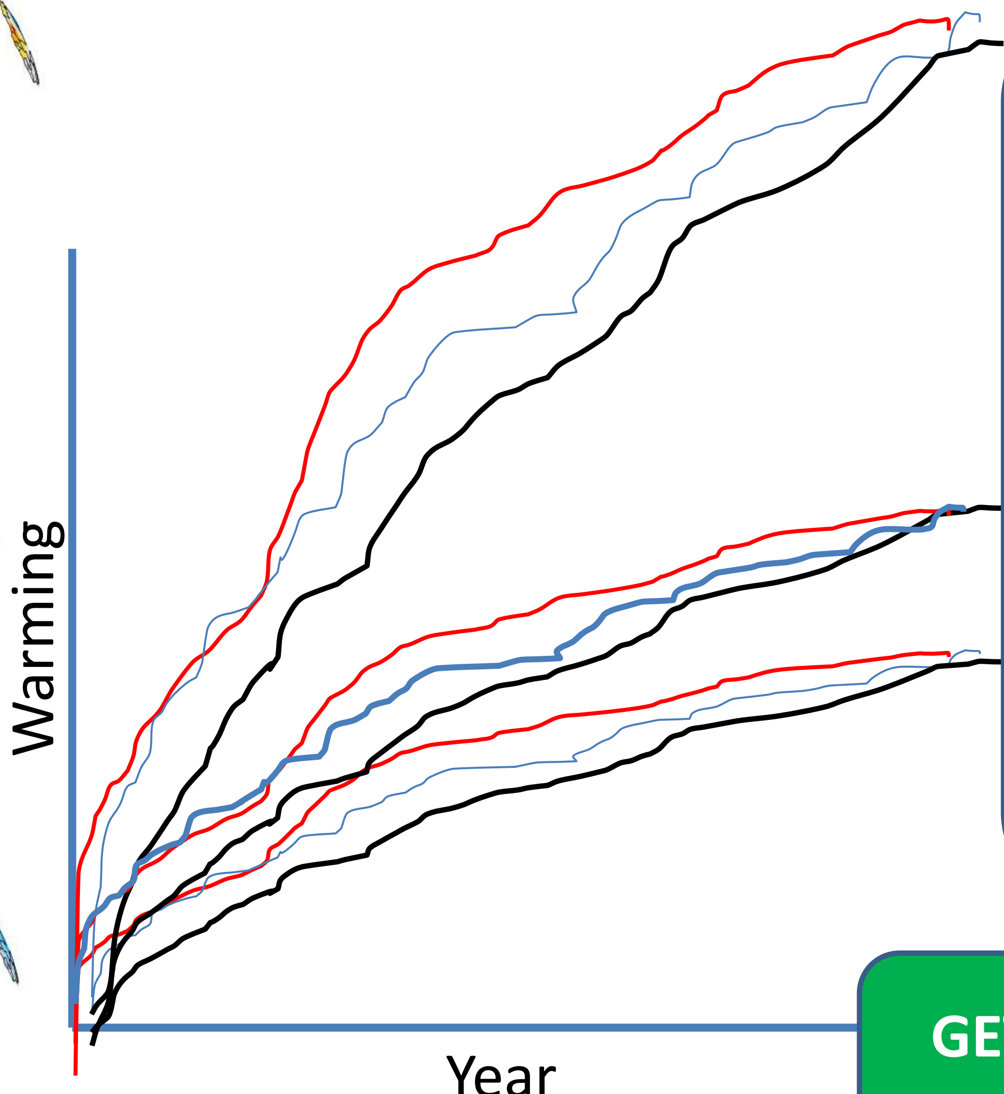
- **Capture total uncertainty**
- **Choose probability constraints for set of DAI's**
- **Find efficient ways to satisfy constraints**

Pricing Carbon at the Margin









Assume values of climate variables

Compute path

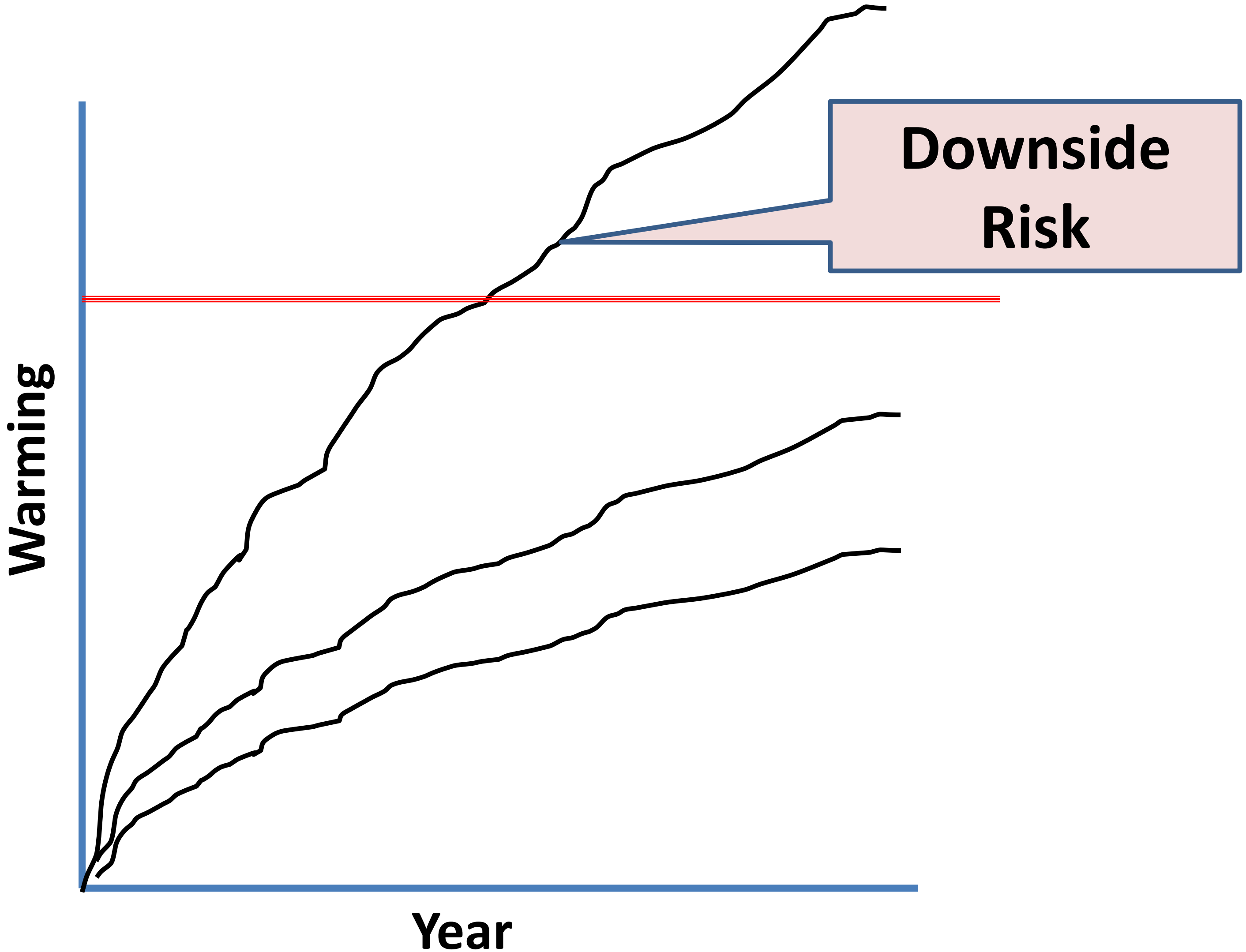
Compute NPV of damages from Δ1 t C

Different damage model

Different SOW

GET distribution over marginal cost of carbon

Buying Down Risk



Model Uncertainty

- Stress test
- Canonical variations

Stress Test DICE Growth Model

Λ = abatement, A = total factor productivity, K = capital stock, N = labor, δ = depreciation

$$\textbf{Output}(t) = \frac{[1-\Lambda(t)]\, A(t)\, K(t)^{\gamma}\, N(t)^{1-\gamma}}{(1 + .0028\,\text{Temp}(t)^2)}$$

$$K(t+1) = (1-\delta)\, K(t) + \text{Output}(t) - \text{Consump}(t)$$

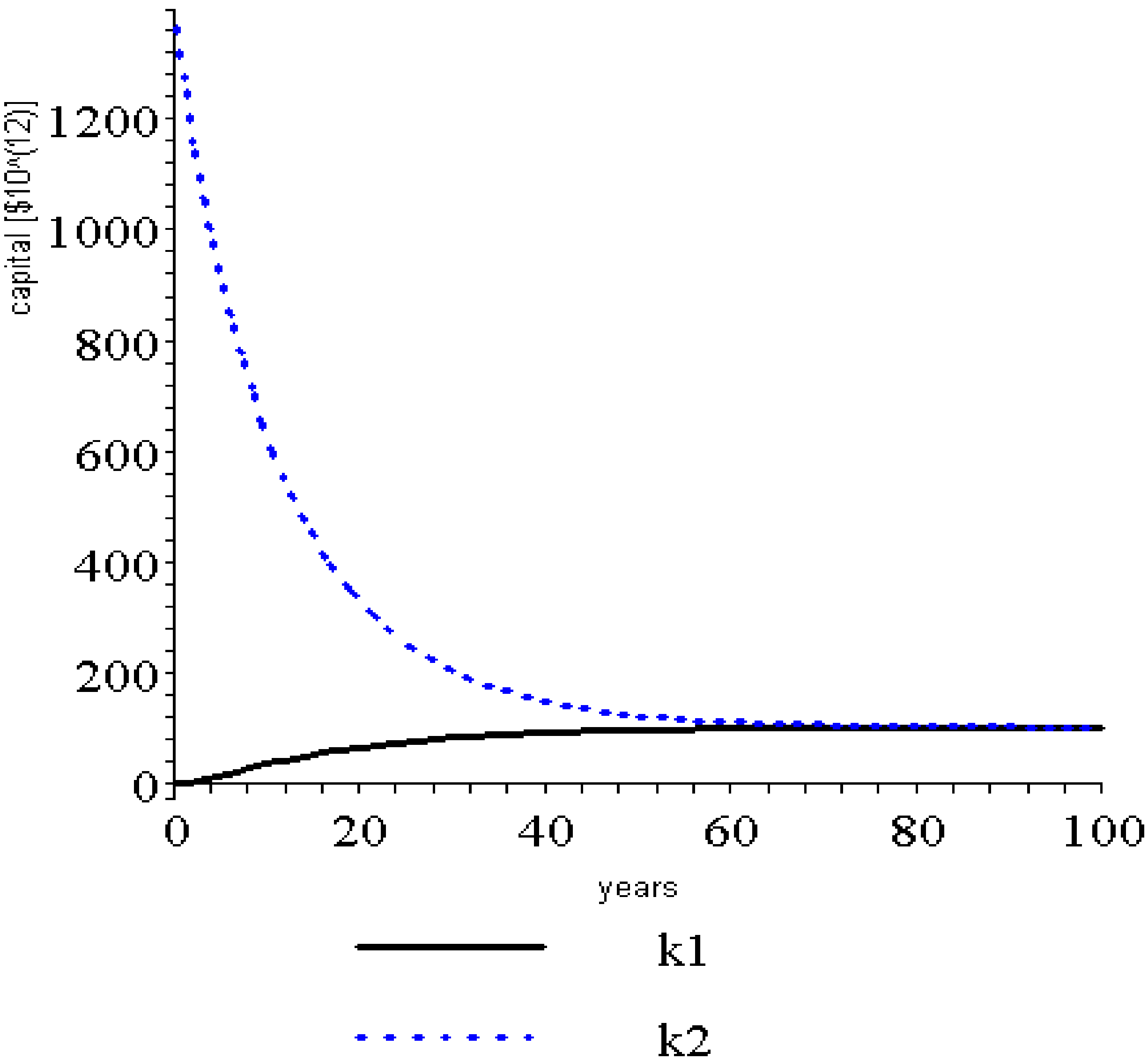
Bernoulli Equation Consump(t)=η(t)Output(t) :

$$dK/dt = -\delta K(t) + B(t)K(t)^{\gamma};$$

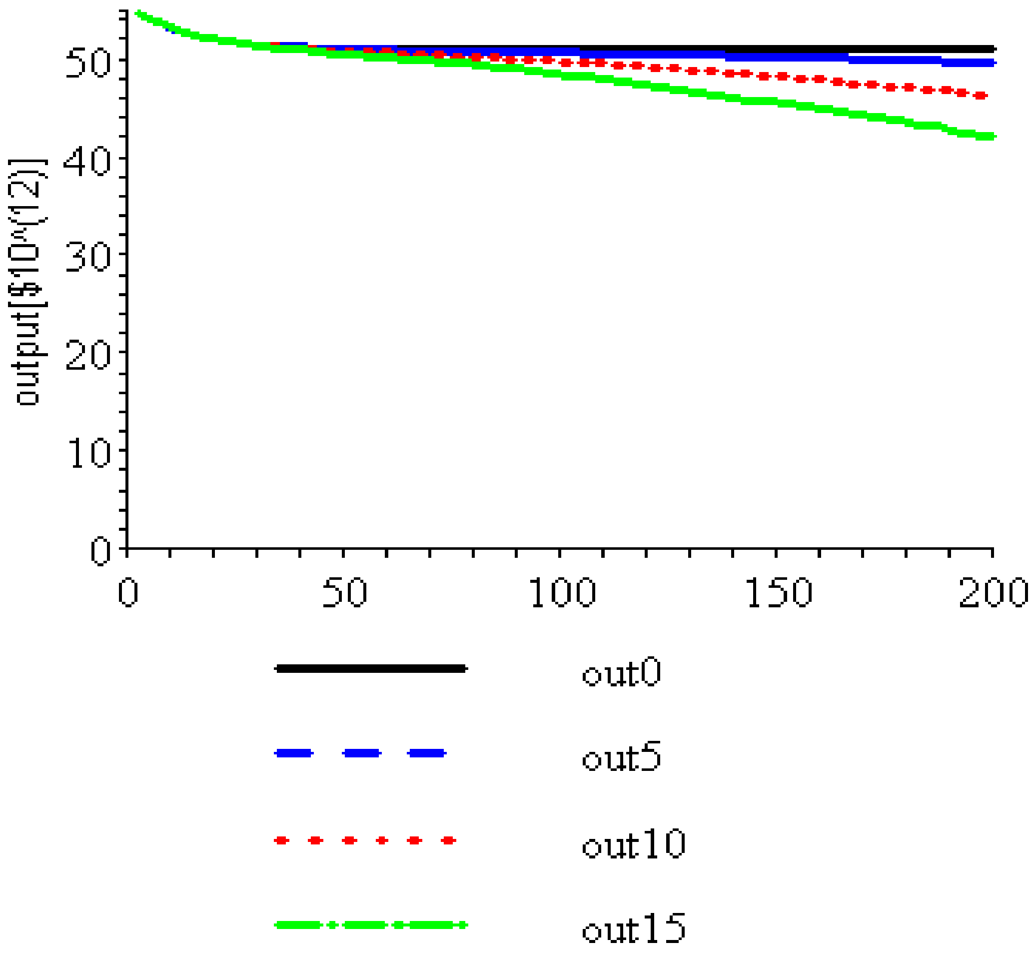
Put Temp(t) $\equiv$ 0; A(t) $\equiv$ A; N(t) $\equiv$ N; Λ(t) $\equiv$ 0; η(t) $\equiv$ η

$$K(t) = [(1-\gamma)\, B\int_{x=o..t} e^{-(1-\gamma)\delta x}\, dx \;\; + e^{-(1-\gamma)\delta t}\, K(0)^{\,(1-\gamma)}]^{1/(1-\gamma)}$$

Two capital trajectories with DICE values, no temperature rise, no abatement K1(0) = 1$ and K2(0) = 1370 trillion $



Output[Trill $], outx(t) is output at time t with linear temperature increase of x [C] in 200 years with starting capital C = 137 [Trill $]



Canonical Variations

- Do other simple model forms

  have structurally different behavior?

Lotka Volterra instead of Bernoulli Model

$$GHG(t+1) = (1-0.0083)GHG(t) + 0.024 \times GWP(t)$$

Emissions proportional to Gross World Output
(Kelly & Kohlstadt 2001)

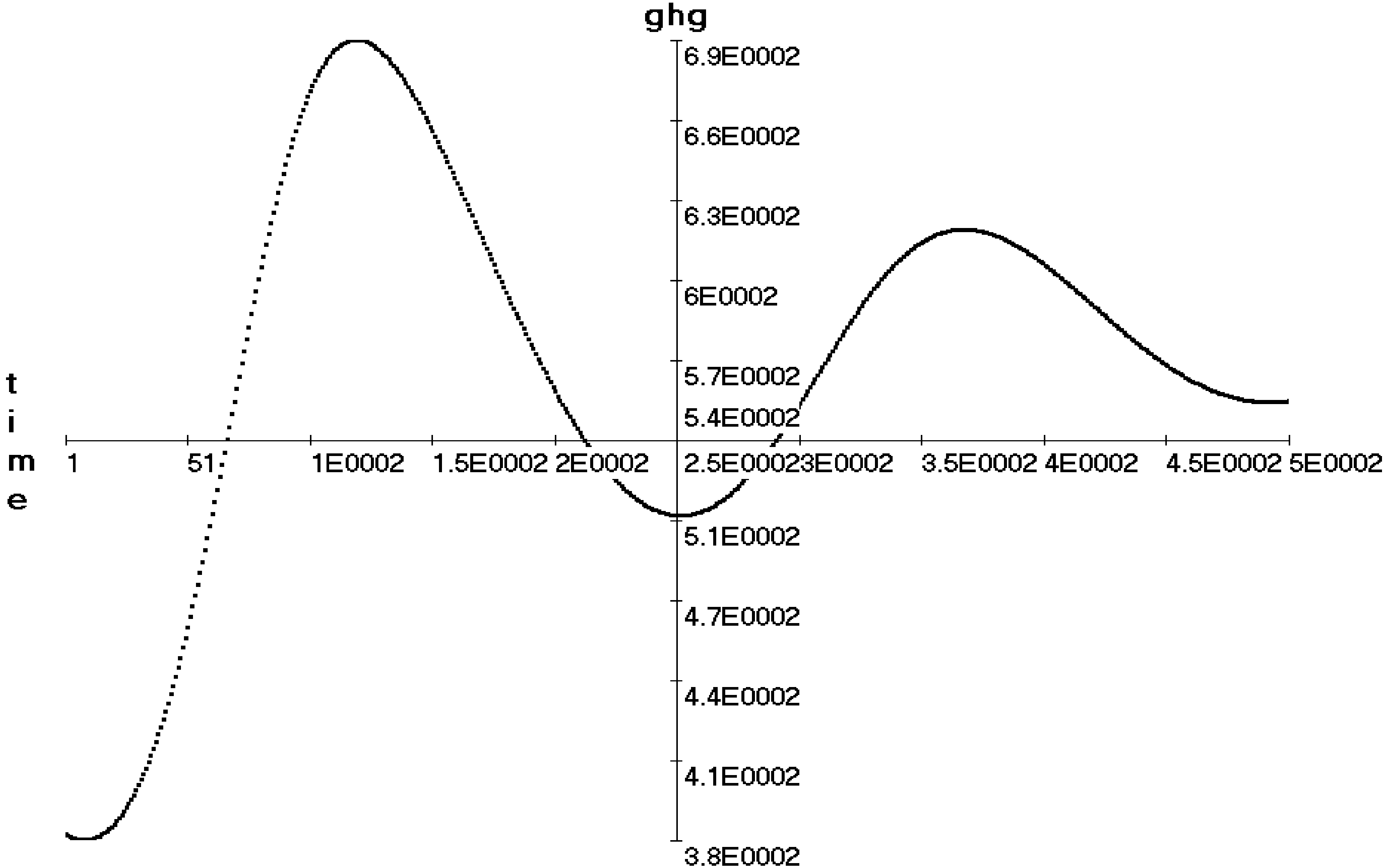
$$GWP(t+1) = [1 + 0.03 - D(T(GHG(t)))] \times GWP(t)$$

Gross World Output Growth Rate
(World Bank, last 48 yrs)

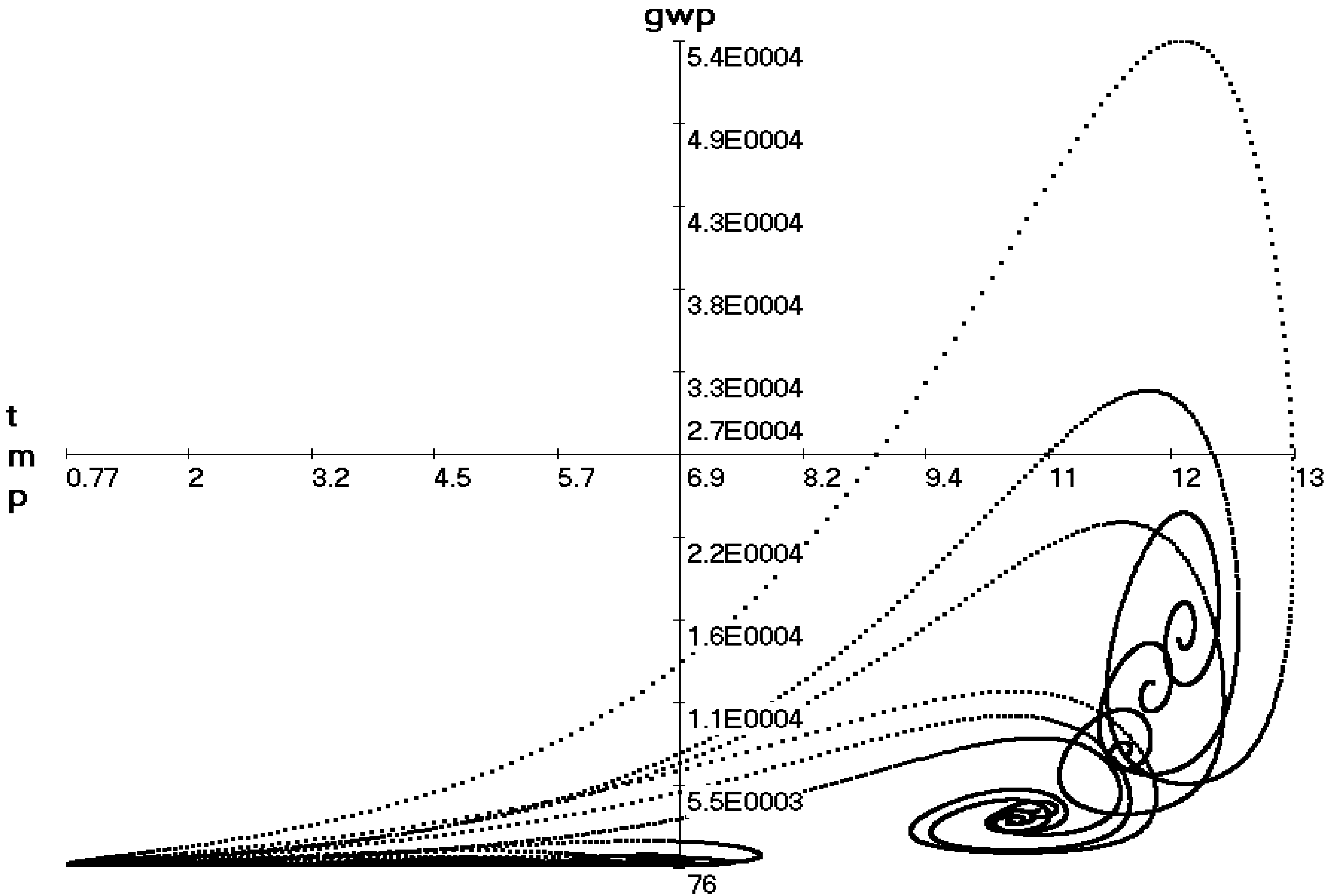
$$D(GHG)(t) = (T/18)^2$$

Weitzman's Death Temperature

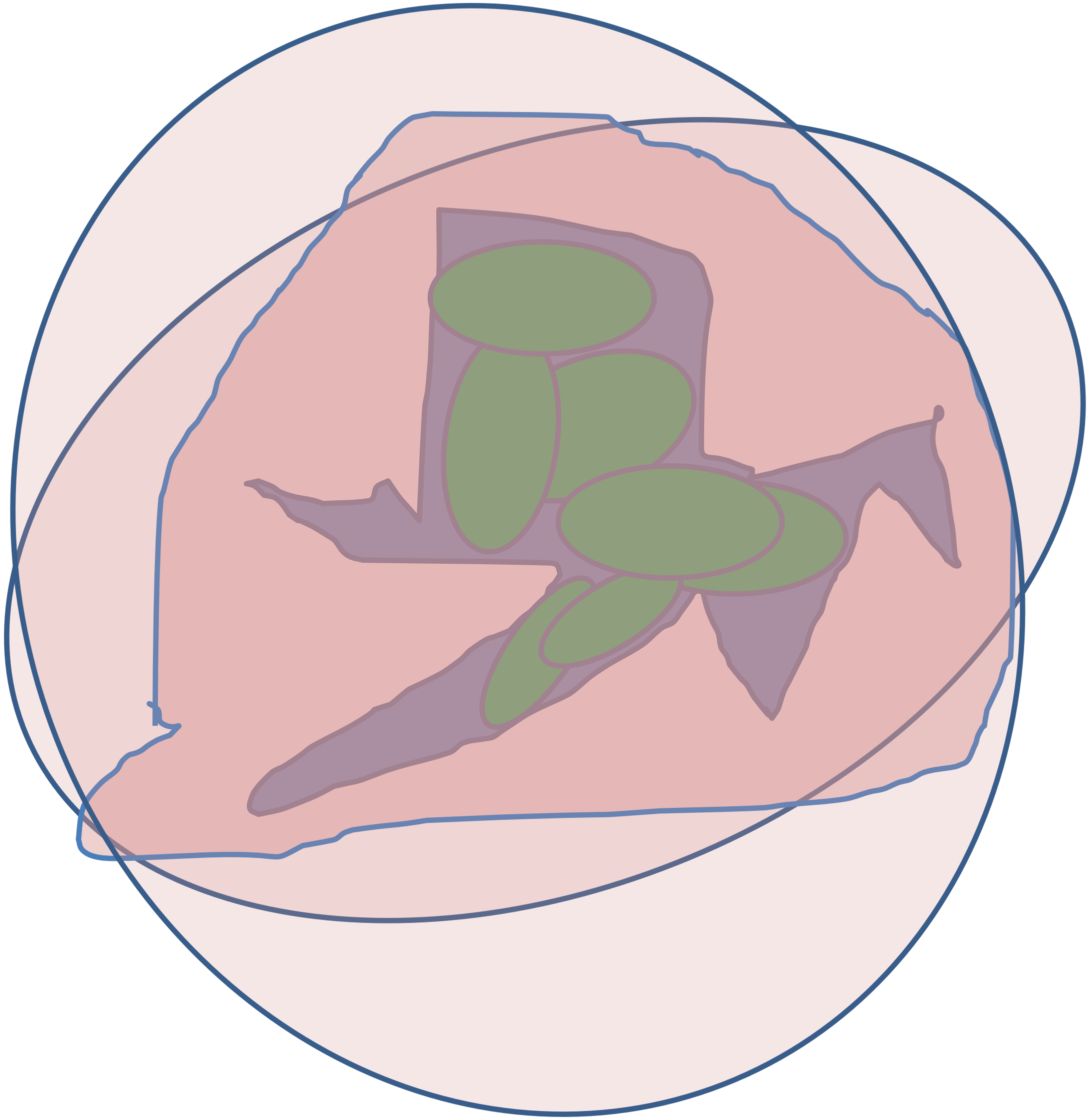
Different Behavior



Phase Portraits, w / wo Dependence



Damage: Inner & Outer Measure



Deal with Model Uncertainty?

- Fit your models to data?
- Fit your models to probabilistic data from Structured Expert Judgment
- Bayes Model Averaging
- ….

Yale G-Econ Database: Gross Cell Product

GCPpp Time average growth rate:

[Ln(GCPpp) – min[lnGCPpp)] / 400

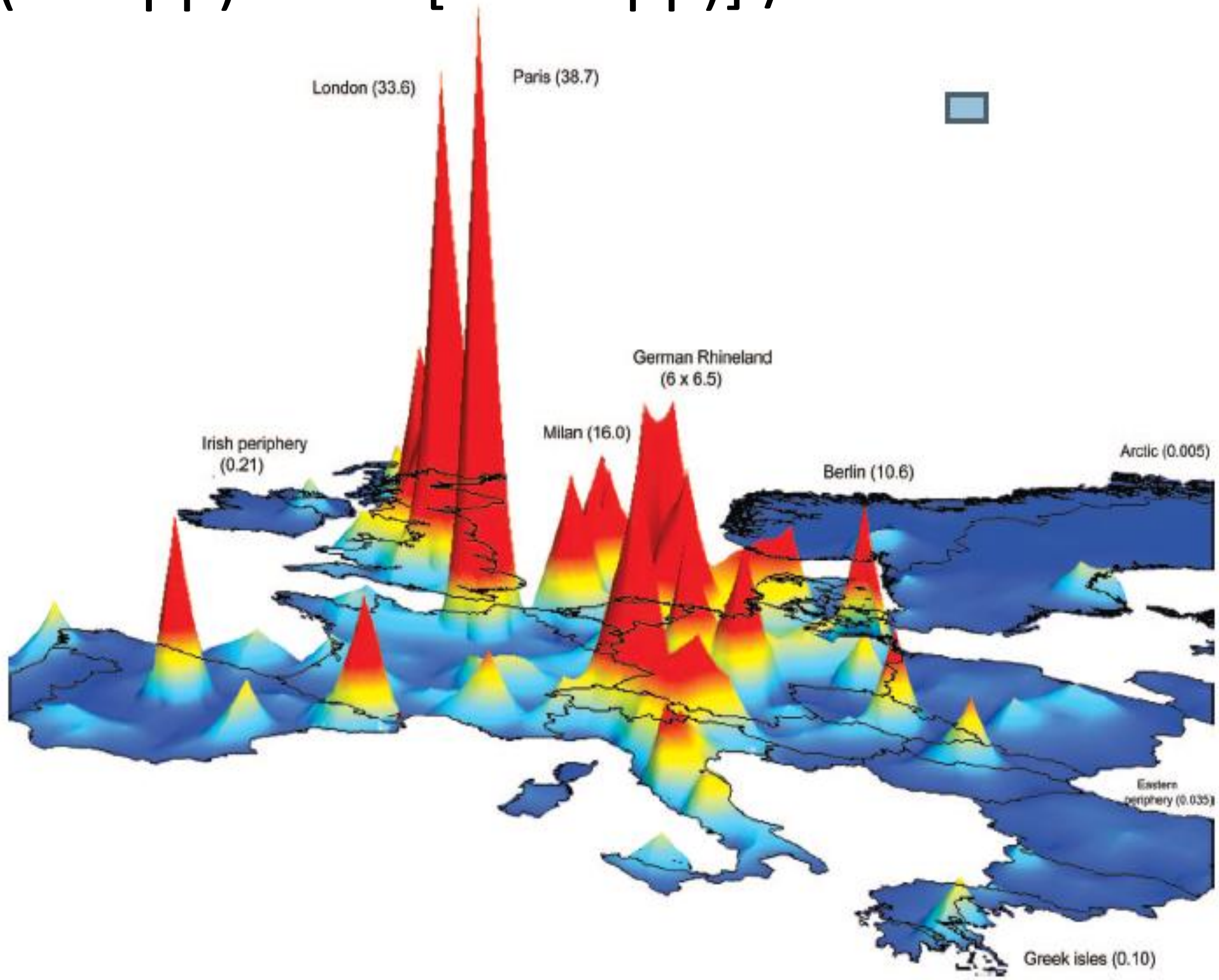
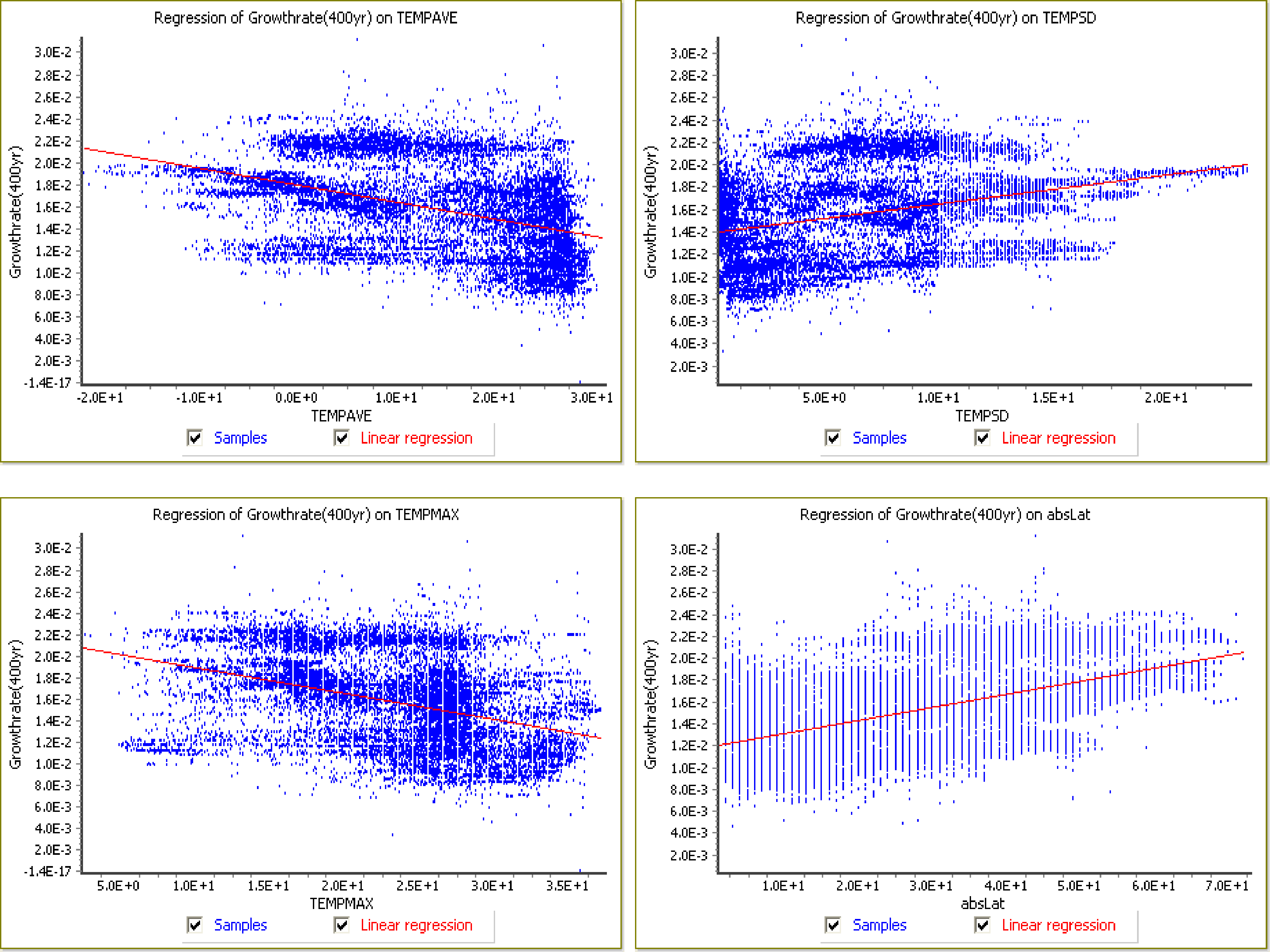
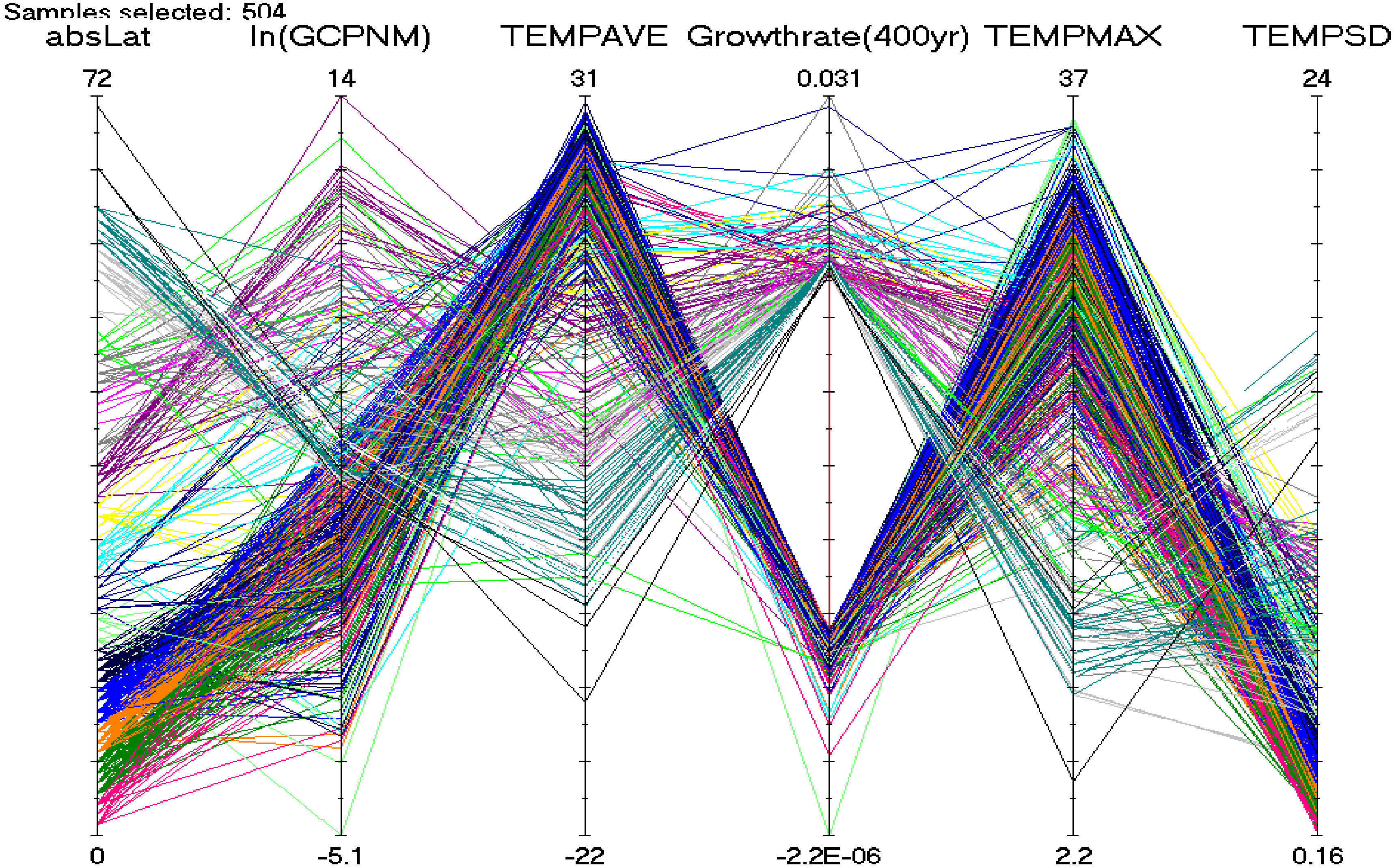


Fig. 1. Economic map of Europe. This figure shows an economic topographical map of Europe with heights proportional to gross domestic product per area
Note how economic activity clusters in the core, whereas the periphery has much lower economic elevations. The observations measure economic activity i
millions of 1995 U.S. dollars per km^2 at a 1° latitude by 1° longitude scale.


Regression of Growthrate(400yr) on TEMPAVE
Growthrate(400yr)
3.0E-2
2.8E-2
2.6E-2
2.4E-2
2.2E-2
2.0E-2
1.8E-2
1.6E-2
1.4E-2
1.2E-2
1.0E-2
8.0E-3
6.0E-3
4.0E-3
2.0E-3
-1.4E-17
-2.0E+1
-1.0E+1
0.0E+0
1.0E+1
2.0E+1
3.0E+1
TEMPAVE
Samples
Linear regression
Regression of Growthrate(400yr) on TEMPSD
Growthrate(400yr)
3.0E-2
2.8E-2
2.6E-2
2.4E-2
2.2E-2
2.0E-2
1.8E-2
1.6E-2
1.4E-2
1.2E-2
1.0E-2
8.0E-3
6.0E-3
4.0E-3
2.0E-3
5.0E+0
1.0E+1
1.5E+1
2.0E+1
TEMPSD
Samples
Linear regression
Regression of Growthrate(400yr) on TEMPMAX
Growthrate(400yr)
3.0E-2
2.8E-2
2.6E-2
2.4E-2
2.2E-2
2.0E-2
1.8E-2
1.6E-2
1.4E-2
1.2E-2
1.0E-2
8.0E-3
6.0E-3
4.0E-3
2.0E-3
-1.4E-17
5.0E+0
1.0E+1
1.5E+1
2.0E+1
2.5E+1
3.0E+1
3.5E+1
TEMPMAX
Samples
Linear regression
Regression of Growthrate(400yr) on absLat
Growthrate(400yr)
3.0E-2
2.8E-2
2.6E-2
2.4E-2
2.2E-2
2.0E-2
1.8E-2
1.6E-2
1.4E-2
1.2E-2
1.0E-2
8.0E-3
6.0E-3
4.0E-3
2.0E-3
1.0E+1
2.0E+1
3.0E+1
4.0E+1
5.0E+1
6.0E+1
7.0E+1
absLat
Samples
Linear regression

Joint Distribution as Cobweb Plot

Conditional on top and bottom 1% growth rates



Factor multiplying GCPpp when changing only TEMPAVE +3C				
	Indep Vbl	**Covariate**	**Partial reg coeff**	**Factor**
Model 1	ln(GCPpp)	TEMPAVE	-0.06167	0.831095973
Model 2	ln(GCPpp)	absLat	0.083428	1.388541617
		TEMPAVE	0.109418	
		TEMPMAX	-0.09706	
Model 3	ln(GCPpp)	absLat	0.088856	0.892180333
		TEMPAVE	-0.038029	
		TEMPMAX	0.047788	
		TEMPSD	-0.222984	
Model 4	ln(GCPpp)	TEMPAVE	-0.121162	0.695248461
		TEMPMAX	0.041572	
		TEMPSD	-0.103743	

Conclusions

- Need to tackle model uncertainty
- Need to converge ‘inner’ and ‘outer’ damage models

What Are Predicted Impacts of Warming?

- 5^oC
  - collapse of Greenland ice sheet
  - large-scale eradication of coral reefs
  - disintegration of West Antarctic ice sheet
  - shut-down of thermohaline circulation
  - millions of additional people at risk of hunger, water shortage, disease, or flooding

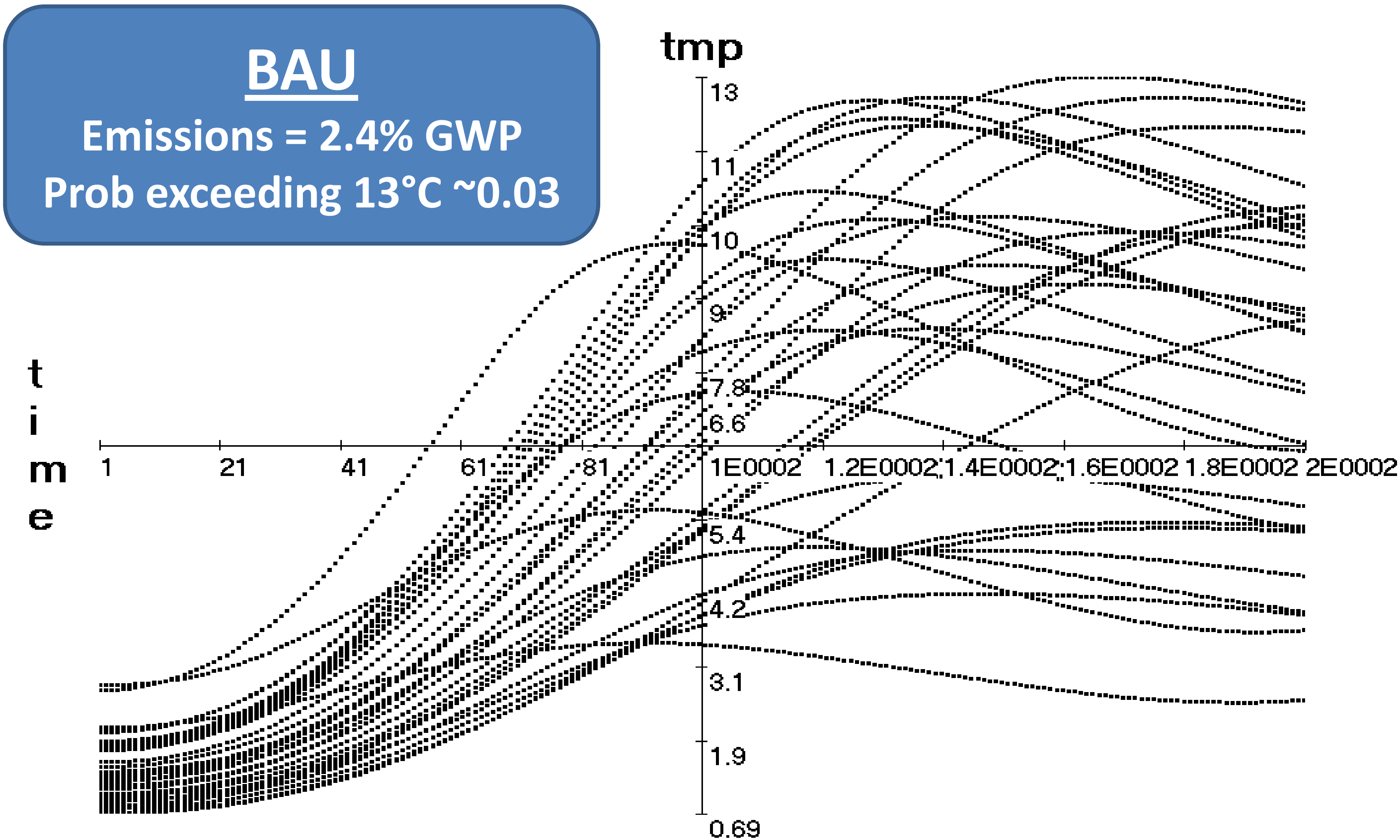
    (Parry, Arnell, McMichael et al. 2001; O'Neill and Oppenheimer 2002; Hansen 2005)

- 11-12°C
  - regions inducing hyperthermia in humans and other mammals "would spread to encompass the majority of the human population as currently distributed"

    (Sherwood and Huber 2010)

Value@Risk *(Basel II Protocol)*

Banks reserve capital to cover "1-in-200 yr" loss event



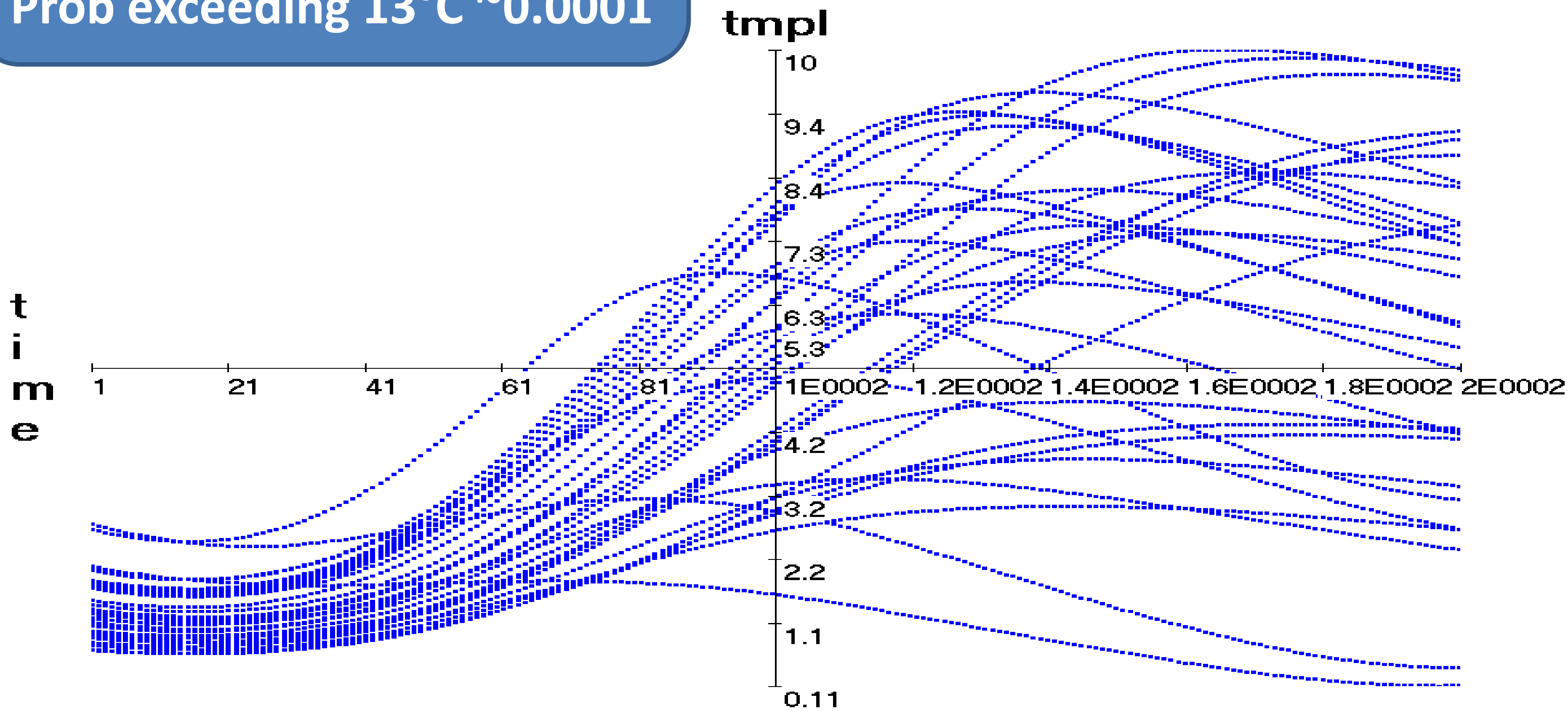
Value@Risk *(Basel II Protocol)*

Banks reserve capital to cover “1-in-200 yr” loss event

Stringent

Emissions = 1.5% GWP

Prob exceeding 13°C ~0.0001



Risk Constraints

- PROB{ $\Delta T > 13°C$ for 500 yr} < 0.0001
- PROB{Greenland ice sheet melts in 300 yr} < 0.001
- PROB{Oceans become net C emitter in 100 yr} < 0.01
- ***What is the price?***