WORKSHOP PROCEEDINGS

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

The Need for a Fresh Approach to Climate Change Economics

Frank Ackerman
Stockholm Environment Institute

Stephen J. DeCanio
University of California, Santa Barbara

Richard B. Howarth
Dartmouth College

Kristen Sheeran
Economics for Equity and the Environment Network

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Workshop Speakers

David Anthoff, Eileen Claussen, Kristie Ebi, Chris Hope, Richard Howarth, Anthony Janetos, Dina Kruger, James Lester, Michael MacCracken, Michael Mastrandrea, Steve Newbold, Brian O'Neill, Jon O'Riordan, Christopher Pyke, Martha Roberts, Steve Rose, Joel Smith, Paul Watkiss, Gary Yohe

Project Directors

Steve Seidel
Janet Peace

Project Manager

Jay Gulledge

Production Editor

L. Jeremy Richardson

Content Editors

Jay Gulledge, L. Jeremy Richardson, Liwayway Adkins, Steve Seidel

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Pew Center on Global Climate Change
2101 Wilson Blvd., Suite 550
Arlington, VA 22201

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The Need for a Fresh Approach to Climate Change Economics[1]

Frank Ackerman[2]
Stockholm Environment Institute
Stephen J. DeCanio
University of California, Santa Barbara
Richard B. Howarth
Dartmouth College
Kristen Sheeran
Economics for Equity and the Environment Network

Abstract

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

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

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

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

1. Introduction

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

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

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

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

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

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

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

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

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

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

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

2. The Discounted Utility Framework and its Implementation through IAMs

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

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

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

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

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

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

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

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

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

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

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

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

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

3. Predicting the unpredictable and pricing the priceless

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

4. Discounting and Uncertainty

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

6. Conclusions

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

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

Abbreviations

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

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