New Directions in the Economics and Integrated Assessment of Global Climate Change

Prepared for the Pew Center on Global Climate Change

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Foreword *Eileen Claussen, President, Pew Center on Global Climate Change*

This report elaborates on four issues — technological innovation, the behavior of firms, intergenerational equity, and climate "surprises" — that have profound implications for the modelers and makers of climate policy. Computer models that integrate climate science, policy, and economic research have become essential to climate change policy discussions. These "integrated assessment" (IA) models are extremely useful for several reasons: they assess specific climate change policies, coordinate the multiple issues in a systematic framework, and provide an analytical method for comparing climate policies to other, non-climate related policies. However, most IA is based largely on economic theories whose simplifications are not always applicable to climate change policy. This paper examines four kinds of assumptions that underlie most IA models, and shows how different approaches more in line with the latest research might change our view of the economics of the climate problem.

The first paper, by Alan Sanstad, focuses on technological innovation and its treatment in IA models. Most models do not incorporate a realistic assessment of how market forces drive innovation. While innovation would clearly lower the costs of addressing climate change, many modelers focus on the *opportunity* cost of encouraging technological progress on climate-friendly technology. The fear is that climate-related R&D will "crowd out" other kinds of R&D. Sanstad's work examines this question, taking into account that the economy systematically underinvests in R&D, and shows that policies promoting climate-related R&D may simultaneously encourage, not discourage, R&D in other sectors.

The second paper, by Stephen DeCanio, discusses how IA models characterize the behavior of firms by assuming they do no more than maximize profits, and that they always succeed perfectly in doing so. This often leads to misunderstandings about: (1) how firms innovate, and (2) the trade-offs firms must make between environmental and economic performance. DeCanio's model describes firms as information networks with multiple objectives, which leads to a more complete picture of how firms innovate. The model also shows that both superior economic and environmental performance can be achieved through technological and organizational innovation.

The third paper, by Richard Howarth, addresses how future generations are depicted in most IA models. Models typically use a single, simple discount rate to make intertemporal comparisons for anywhere from 50 years to sometimes 300 years into the future. But over very long periods of time, these comparisons involve different generations of people. Howarth accounts for these differences using the so-called "overlapping generations" models — a model that incorporates the detail of IA models while providing a more realistic assessment of each generation's spending and savings behavior. This work indicates that policies inclined towards climate stabilization provide an "insurance" policy that protects future generations against potentially catastrophic costs. Even if damage costs turn out to be moderate, Howarth finds, emissions control is still consistent with maintaining long-term economic well-being.

Stephen Schneider and Starley Thompson, in the final paper, provide a new model to explore the causes and consequences of one major type of "climate surprise" — the collapse of the "conveyor belt" circulation of the North Atlantic Ocean. Climate "surprises" are the low-probability but high-consequence scenarios driving much of the international concern about climate change. Currently, most IA models assume the climate responds slowly and predictably. The authors find IA models that ignore the implications of rapid, non-linear climatic changes or surprises are likely to overestimate the capacity of humans to adapt to climatic change and underestimate the optimal control rate for GHG emissions. The conclusion is that it is critical that the full range of plausible climatic states become part of IA policy analysis.

This report is the latest in the Pew Center's economics series. As with the rest of the series, these reports will help to demystify the models and explain what type of questions they can (and cannot) answer. But whereas until now we have focused on what has been done in the past, we now begin to focus on what needs to be done in the future. This report includes four critiques of the assumptions underlying IA, and suggests ways in which new and improved models could provide greater insights into what policies would be most efficient and effective in reducing greenhouse gas emissions:

- IA models that more accurately portray innovation will help policy-makers answer questions such as the following: Should the government subsidize climate-friendly R&D? Will increasing carbon prices alone drive sufficient innovation to solve the GHG problem? How should we time and phase emission reductions to take maximal advantage of technological progress?

- IA models that more realistically portray businesses will make it clear that the challenge for policy-makers is to find ways to encourage businesses to innovate in multiple dimensions to meet multiple objectives.
- IA models that take into account the standpoint of future generations will enable policy-makers to explicitly consider the implications of policy for equity as well as efficiency.
- IA models that can explore the causes and consequences of "climate surprises" will help policy-makers to understand the implications of speeding up or slowing down the rate of greenhouse gas buildup, which may turn out to be as important as the size of the buildup.

Earlier versions of the papers in this report were first presented during the Pew Center's July 1999 economics workshop, which convened leading experts to discuss potential improvements to current IA modeling methods. The insights of participants in that workshop were invaluable.

This report benefited greatly from the comments and input from several individuals. The Pew Center and authors would like to thank Kenneth Arrow, Larry Goulder, Robert Lind, Klaus Hasselman, and Bruce Haddad. Special thanks are also due to Ev Ehrlich and Judi Greenwald for serving as consultants on this project.

I. Introduction

Our knowledge of the global climate system, and of how human actions may be changing it, is the product of a large and expanding body of scientific research. Translation of this knowledge into policies for dealing with the possibility of global climate change, however, has been largely carried out using the concepts and methods of economics. Unique among the social sciences, modern economics provides a set of powerful analytical and computational tools that support quantitative modeling of economy- and society-wide policies over the long run. The formidable challenges posed by the complexity of climate policy have made economic modeling an especially attractive means of organizing and applying a range of scientific, economic, and social research to analyzing how we should respond to the threat of climate change.

In practice, such analysis is typically carried out through the construction and application of large-scale computer models that combine scientific and economic theories and data into unified quantitative frameworks. These "integrated assessment" models have emerged as decision-makers' primary tool for quantitative climate policy analysis.

In keeping with their origins, integrated assessment models (IAMs) are commonly built on the principles of what is often referred to as "standard" or "conventional" economic theory. The papers in this volume deal with four of the key assumptions underlying this theory as it has typically been applied to climate economics and integrated assessment. The first assumption is that technological change — increases in outputs of goods and services without increases in productive inputs — originates outside of the economy itself; in other words, technological progress is "exogenous" with respect to the market economy. The second is rational behavior on the part of consumers and firms. Colloquially, this is usually thought to mean no more than "enlightened self interest." In the theory and its applications, however, "rationality" is a considerably stronger assumption. It means complete optimization by economic agents over all possibilities open to them in the choice of commodities and actions: nothing is ignored or misunderstood, and no mistakes are made. The third assumption is that economic rationality takes into account all future as well as present possibilities: agents have perfect foresight infinitely far into the future. In practice, this assumption is represented by an infinitely-lived decision-maker, a representative consumer, or a social planner, who optimizes over a completely foreseen infinite horizon.

The final assumption has to do with the representation of the "externalities" or deleterious effects that could arise from climate change. The common approach in integrated assessment is to represent climate-related externalities as a function of the total stock of greenhouse gases (GHGs) in the atmosphere. A key conclusion of this method is that the climate problem is fundamentally "slow-moving," and that even "large" anthropogenic emissions constitute only "small" additions to the global GHG stock at any given time, so the total stock changes slowly relative to the time-scales on which policies are usually formulated.

These assumptions — exogenous technological change, rational behavior, the infinitely-lived agent, and the basic stock externality model of GHGs — are fundamental design principles underlying standard climate economics and almost all integrated models. The papers here report on the results of research in which these fundamental elements are altered and the resulting implications for climate policy modeling are analyzed. The first paper, by Alan Sanstad, considers the consequences of recognizing that technological change is not typically "exogenous" but rather is strongly influenced by market incentives. In the second paper, Stephen DeCanio explores what happens when the basic rationality assumption as it applies to firms is replaced by a model in which firms are viewed as complex communication networks that do not engage in the fully-informed, optimal decision-making posited in the neoclassical model. In the third paper, by Richard Howarth, the infinitely-lived decision-maker is replaced by a series of distinct demographic generations. In the concluding paper, Stephen Schneider and Starley Thompson describe a model that can display abrupt, non-linear changes in the ocean-atmosphere system as a result of increased carbon dioxide (CO_2) concentrations. These particular ideas constitute a sampling, in effect, of important recent developments in economics and climate science that warrant application to climate policy and integrated assessment modeling. The aim is to indicate several directions in which integrated assessment can and should develop in order to better enable policy-makers and citizens to grapple with the daunting risks and challenges posed by global climate change. The sections below provide a brief introduction to these topics.

A. Endogenous Technological Change

The standard models rule out the possibility of entrepreneurial responses to climate policy — the new innovation aimed at carbon reductions that would arise in response to new incentives. This innovation would be a form of "endogenous" technological change, in that it would occur within the economy in response to market forces. This omission raises the possibility that the models as currently structured systematically overestimate the costs of carbon abatement because they do not account for the accelerated carbon- or energy-saving innovation that would result from price-based carbon reduction policies.

In the past two decades, economists have made considerable strides in modeling the underlying processes of technological change and economic growth, focusing on how technical innovation arises within a market economy in response to economic incentives. This work — the "new growth theory" or theory of "endogenous technological change" — has been recognized as potentially significant for climate policy, and in recent years several initial applications have appeared. Sanstad discusses the key ideas of this theory and several of its applications to climate policy in the first paper.

As Sanstad describes, economists acknowledge (and partially confirm) the cost-saving potential of endogenous technological change. However, they have also emphasized the losses that would arise from reallocating resources such as human expertise to new carbon- or energy-saving innovation and away from other applications. For example, as engineers turn their attention to energy efficiency and away from other activities, there could be a slow-down of technical innovation in other sectors. Alternatively, there would be costs associated with training new engineers. It has been suggested that such opportunity costs of stimulating new "climate-friendly" technical change would be sufficiently large to nearly or completely offset the benefits.

Sanstad notes, however, that the modeling of technological change as an endogenous phenomenon is closely linked with the finding that the market system may systematically under-invest in innovation. This effect results from the "public good" character of knowledge as an economic commodity: the use of an idea by one does not preclude its use by another. The new growth theory provides tools for the rigorous analysis of this phenomenon in the general equilibrium setting necessary for applications to integrated assessment. Sanstad shows that, when this finding is taken into account, the opportunity cost problem may be substantially mitigated. In fact, it may be the case that policies to speed up one form of innovation would actually also speed up competing forms. These results follow from the fact that the economy's initial equilibrium may allocate too few resources to innovation overall, so that policies that encourage a specific form of innovation may improve overall economic efficiency. As he discusses, this conclusion rests on the empirical question of the degree to which the new growth theory's prediction of under-investment in research and development (R&D) is borne out in practice. This question is thus a key priority for further research.

B. The Theory of the Firm

Within the economics community there has been a lively and long running debate on the nature of the firm and assumptions regarding the degree to which the typical firm's behavior can be characterized as "rational." Beginning with the work of Herbert Simon in the 1940s and 1950s, there has been a steady expansion of theoretical and empirical efforts to open up the "black box" of the profit-seeking private sector firm to better understand how companies actually behave in a market economy. In the second paper, DeCanio summarizes several aspects of the modern critique of the neoclassical theory of the firm that have a bearing on integrated assessment issues. The questionable elements of neoclassical theory include: (1) the assumption that firms have a unitary objective — profit maximization — rather than the multiple objectives they are known to pursue; (2) the exclusive focus on the firm's selection of how much of each aggregate "factor of production" (land, labor, capital, materials) to employ, when these choices actually occupy only a small portion of managers' time and attention; (3) the assumption that technological change arises from "exogenous" factors, independent of the activity of the firm, instead of its being in large part a product of the procedures and decisions of the firm; and (4) the premise that firms always make optimal decisions, rather than, as in reality, searching for improvements in an environment too complex to allow full optimization.

DeCanio goes on to describe modern advances in the theory of the firm from fields such as the new institutional economics and management science, showing how these ideas could improve the treatment of firms in integrated assessment. He describes how these alternative frameworks call into question the conventionally assumed trade-off between environmental quality and the production of other goods. Instead, he argues for a perspective in which these two objectives are complementary.

DeCanio next presents results from the application of a mathematical "network" model of organizational structure and evolution that contrasts sharply with the neoclassical model. The premise of the network model is that patterns of communication and control within the firm are fundamental to understanding the dynamics of decision-making. Accordingly, the focus is on the behavior of the firm as an *information processing system* that is capable of "learning" over time in the sense of establishing new internal patterns of communication links. The model is explicitly economic in that it includes the costs associated with establishing and maintaining communications within the firm. This richer representation makes it possible to analyze rigorously phenomena that are essentially ignored in the neoclassical framework.

Among the most important of these phenomena is the manner in which the firm evolves in order to improve its performance on specific tasks — such as adopting a profitable technological innovation (e.g., in energy efficiency). All else being equal, increasing the density of communication links yields an economic gain to the firm; at the same time, however, it carries a commensurate cost. Thus, the organizational structure arrived at by an evolutionary process will depend on the particular form and parameters of the cost and reward functions. As a result, there will in general be no single "optimal" internal organization for the firm that prevails under all circumstances: the result of evolutionary learning will depend on the changeable nature of the firm's tasks and opportunities. In addition, the evolutionary course of a firm's development is likely to depend on the path it takes, with multiple outcomes — having roughly equal profitability but different organizational structures — possible.

One corollary of these findings with particular significance for environmental policy is that different organizations may be comparable in profitability but can exhibit very different environmental behaviors and impacts. This means that improvement in environmental performance is possible without sacrificing overall profitability. In essence, the trade-off between profitability and environmental protection dissolves.

C. Intergenerational Fairness and Efficiency

One of the most basic features of global climate change is that while the present generation is deciding what if anything to do about it, the impacts of climate change (and hence the consequences of today's actions or inaction) are likely to be borne by future generations. Cost-benefit analysis that ignores the standpoint of future generations sidesteps some of the issues of fairness and equity associated with climate change, notably including the risks that today's lifestyles and technologies may be imposing on posterity through GHG emissions.

In the third paper, Howarth conducts a quantitative analysis that emphasizes the differential impacts that climate change response strategies would have on the welfare of present and future generations. This analysis employs a so-called "overlapping generations" (OLG) model, which posits (as the name suggests) a succession of generations. OLG models were pioneered in the 1950s by Paul Samuelson, and have since become a mainstay in the field of public finance, where they are used to study the impacts of taxation and government debt on the distribution of income between generations. This framework, however, has not been widely used in climate policy modeling.

Howarth uses an OLG-based IAM to compare the impacts of three policy regimes on the welfare of present and future generations. In the first scenario — the *laissez-faire* base-case — the economy is managed according to free-market political precepts, and no steps are taken to reduce GHG emissions. Over the long-term future, this scenario yields an increase in mean global temperature of 8.0 ºC relative to the pre-industrial norm, which imposes costs on future generations equivalent to 9 percent of economic output. In the second scenario — *cost-benefit analysis* — conventional economic criteria are used to balance the present costs and expected future benefits of climate change mitigation measures. In this scenario, future environmental benefits are discounted relative to the present, so that only modest steps are taken to reduce GHG emissions. Relative to the *laissez-faire* baseline, the emissions control rate rises from 15 to 23 percent between the years 2000 and 2105. These reductions provide relatively small environmental benefits to future generations.

In the third policy scenario — *climate stabilization* — GHG emissions are reduced to the levels required to maintain mean global temperature at its current level, which requires a GHG emissions tax that rises from $560 per metric ton of carbon in the year 2000 to $1,081 in the long-term future. Although critics claim that such aggressive policies might "lock up" the resources required to sustain a productive economy to the detriment of both present and future society, Howarth's analysis reaches a rather different conclusion. In comparison with the *laissez-faire* and cost-benefit scenarios, climate stabilization reduces short-term consumption by 7 percent. In the long run, however, climate stabilization confers welfare gains of $6.4 trillion per year on members of future generations in comparison with the *laissez-faire* baseline, or $2.4 trillion per year relative to the cost-benefit scenario.

This analysis suggests that although GHG emissions are an important contributor to short-term economic welfare, sustained climatic stability may be viewed as an economic asset that would contribute strongly to the welfare of future generations. The results highlight the importance of moral considerations in the identification of "optimal" policies, finding that conventional cost-benefit analysis tends to favor the interests of present producers and consumers at the expense of future society.

D. Climatic Nonlinearities

The standard assumption in most IAMs is that the climate responds slowly and predictably, gradually warming as atmospheric GHG concentrations increase. Recent research on the long run behavior of the climate, however, has focused attention on the possibility of quite different climate dynamics. It is possible that, in fact, the climate may be subject to very rapid changes or "nonlinearities." An important example of this kind of behavior has to do with the Atlantic thermohaline circulation, or "conveyor belt." This is the natural process by which warm water moving northward from the Gulf stream into the Atlantic Ocean transports heat from more southerly latitudes, thereby increasing the temperature of the North Atlantic region. It is now thought possible that this conveyor belt might collapse under certain scenarios of anthropogenic CO_2 emissions, rapidly altering the global climate and profoundly changing the climate in western Europe.

Determining how climate policies should take into account this possibility is clearly a high priority for integrated assessment modeling. Full computer models of the global climate system are far too large and complex to be embedded in IAMs containing economic detail. Indeed, the trend in climate modeling is toward super-computer-run models with integrated atmosphere, land, and ocean sub-models.

Thus, economic IAMs have generally incorporated highly simplified representations of the global climate. The immediate challenge is thus to capture these more complicated dynamics in a simplified form that is amenable to linkages with economic models. In the fourth paper, Schneider and Thompson describe the results of such an effort, a "Simple Climate Demonstrator" (SCD) model. Technically, SCD is a simplified model of the northern hemisphere atmosphere-land-ocean system. Overall, the model replicates the behavior of more elaborate climate models. Schneider and Thompson study the conditions under which a conveyor belt collapse would occur, and find that the probability of this event is increased by: (1) greater CO_2 concentrations, (2) higher rates of increase in CO_2 concentrations, (3) greater sensitivity of the climate to CO_2 concentrations, and (4) assumption of a weaker initial circulation. These findings confirm that IAMs with simpler representations of the climate may not be appropriate for studying the policy implications of rapid climate shifts. It also provides an alternative means of representing such shifts that is sufficiently complex to capture the behavior of more complex climate models while being sufficiently simple for applications to integrated assessment. Preliminary analyses coupling the SCD model to the Nordhaus 1992 Dynamic Integrated Climate Economy (DICE) model demonstrate that the potential for severe climatic damages as a result of non-linear climatic behavior in the twenty-second century and beyond can have a substantial influence on present climate policy decisions if discount rates are below 2 percent (Mastrandrea and Schneider, submitted).

E. Summary Remarks

Integrated assessment modeling is still in its early stages. Because it is by nature an interdisciplinary endeavor, it is ultimately based on the ideas and methods of its constituent disciplines. To date, IAMs have drawn most heavily on neoclassical economics, which is well developed and lends itself to this kind of application. As integrated assessment matures, it will need to broaden its scope to incorporate key ideas at the frontiers of research in economics and in other fields. In this volume, several such ideas are presented. The hope is that these papers will serve to advance discussion and applications that will contribute to the evolution of the integrated assessment modeling of global climate change.

II. Endogenous Technological Change and Climate Policy Modeling

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A. Introduction

The conventional economic approach to climate policy focuses on the use of emissions taxes or tradable emissions permits,[2] *or a combination thereof, to achieve efficient reductions in GHG output.* These policies increase the price of carbon-intensive energy sources, causing consumers and firms to substitute less-expensive alternatives. At the same time, in the standard approach, underlying "autonomous" (i.e., independent of price) reductions in energy use and carbon output would continue unaffected by the introduction of taxes or permits. Substitution and autonomous trends are the two mechanisms by which the economy would move to a lower-carbon path.

This paradigm, however, does not take account of an important additional factor: the incentives to create new carbon-saving or energy-efficient technologies that would result from a carbon price premium.[3] That is, these policies would yield new profitable opportunities for climate-protecting technological innovation, because they would increase the value of technologies that use less carbon or energy. By exploiting these opportunities, entrepreneurs would increase the *rate* of carbon-reducing technological change in the economy. This would constitute a third mechanism for reducing the costs of lowering carbon emissions, in addition to substitution and to the workings of autonomous trends. One could thus hypothesize that the omission of this "entrepreneurial" factor in the standard economic analysis of climate policy could result in overestimation of the costs of carbon abatement.

At the same time, however, the possibility of an entrepreneurial response to climate policy raises yet another question: would encouraging researchers and other innovators to invent new ways to reduce carbon emissions slow down technological change in other sectors? At any given time, there are only so many technologically sophisticated workers to go around. One might thus expect that an indirect cost of speeding up carbon-reducing innovation would be a "crowding out" of innovation elsewhere in the economy. More generally, additional inventors or engineers might be trained, but this training would require a diversion of resources from consumption or investment elsewhere in the economy. Thus, in any case, there would be an opportunity cost resulting from increased "climate-friendly" innovation spurred by new incentives to reduce carbon.

This line of questioning leads directly to a connection between climate policy modeling and the frontiers of current research on economic growth and technological change. Since the mid-1980s, economic theorists have focused on modeling technological change as an activity of profit-seeking agents in the economy, and on the implications of this approach for thinking about the long run evolution of market economies. This work is known generically as the "new growth theory," "endogenous growth theory," or the theory of "endogenous technological change." It arose from theorists' dissatisfaction with the standard or neoclassical model, in which technological change comes from outside the actual workings of the market system, that is, autonomously or "exogenously." While many of the issues involved remain controversial and are the subject of active research, the new growth theory has nonetheless provided an important new set of concepts and methods for analyzing long run technological change and economic dynamics.

Many researchers in the climate policy arena have recognized the potential importance of this work for analyzing the climate problem, but applications have been slow to appear, in part because of the technical challenges of the new methods. This paper summarizes some initial efforts in this direction, emphasizing the opportunity cost question described above. It begins with an overview of the key ideas of both the standard and "new" theory of economic growth and the nature of technological change. It goes on to describe how these ideas relate to the question of modeling technological change — specifically involving energy efficiency and alternative energy sources — in economic models of climate policy. Next, it reviews several specific applications of new growth theory ideas to the climate problem. The paper concludes with a summary and remarks on the implications of this research.

B. Economic Theories of Growth and Technological Change

In everyday life, technological change means specific product improvements and the introduction of new products. The obvious example is information technology: large mainframe computers were followed by personal computers, which have been followed by the World Wide Web — all the while accompanied by constant innovations in software. Economists, however, take a more abstract perspective with the aim of understanding the underlying determinants of this kind of change. Why does innovation occur in the first place? How effectively does the free market promote it? Are government policies needed to encourage it?

To address these kinds of questions, economic theories of technological change begin with fundamental ideas about the nature of commodities and how they are produced and sold in markets. Standard theory characterizes commodities in terms of the concepts of "rivalry" and "excludability." A commodity is rival if its use by one person precludes it use by any other, and excludable if its use can be circumscribed, for example, by the establishment of property rights or other institutional arrangements. Conventional economic commodities are both rival and excludable (or "private"), and a fundamental theoretical insight is that the market or price system produces and allocates optimal or efficient quantities of these.

However, commodities can be non-rival or non-excludable or both. A common example of non-rivalry is national defense: the protection any individual receives from the provision of national defense does not reduce the level of protection received by other individuals. Non-excludability, in turn, characterizes many forms of environmental pollution; it is often not possible to prevent the involuntary "consumption" of pollutants by those who are not involved in their production. Commodities that are non-rival are known as "public commodities," while those that are non-excludable are called "externalities." Economic theory states that the market or price system will in general not produce efficient or optimal quantities of public goods or externalities. Specifically, it will produce too little of "goods" such as national defense and too much of "bads" such as environmental pollution.

The key example of a public commodity underlying the theory of economic growth is that of knowledge or ideas. Many people can use a design for a product. In general, technological knowledge can be thought of as a public commodity, available throughout the economy to all who wish to apply it.[4]

The conventional or neo-classical theory of technological change and economic growth, founded by Robert Solow (1957) in the 1950s, conceived of technological knowledge as a public good, but one arising outside of, or “exogenous” to, the economy. Because of this exogeneity assumption, in Solow’s model there is no economic inefficiency associated with knowledge — in spite of its public character, it is not undersupplied by the market. This assumption allowed Solow to maintain the framework of “perfect competition,” the standard neoclassical paradigm of economic equilibrium. In perfect competition, all commodities are produced at their optimal or economically efficient level. In addition, firms and consumers are “price-takers”: they have no market power (as would, for example, a monopolist) to set prices above competitive levels.

Solow demonstrated theoretically that in the long run, economic growth is possible only through continuing technological change — that is, continuing emergence of new knowledge — or through population growth. However, because both technological and population change were assumed to originate outside of the market economy, economic policy could have no effect on growth in the long run. More generally, in Solow’s model the decentralized economy is fully efficient — government policy cannot improve on “*laissez-faire*” outcomes. Solow’s approach dominated macroeconomic research on technological change and economic growth from its introduction through the 1970s.

In the 1980s, Paul Romer (1986, 1990), Robert Lucas (1988) and others introduced a different approach to the study of economic growth and technological change, based on an alternate treatment of the sources and role of knowledge in the economy. This new growth theory builds on the recognition that to a large extent technological progress arises from the efforts of profit-seeking agents within the economy, that is, it is “endogenous” to the workings of the market system. Put differently, this approach embodies the fact that technological innovation is an *economic* activity. Knowledge is treated explicitly in this framework as non-rival and either fully or partially excludable. One firm’s use, for example, of a design for a new product does not physically preclude its use by another, but its use can be partially restricted through the patent system or other means. These features — the non-rivalry, non- or partial-excludability and endogenous nature of knowledge — entail a departure from the standard assumption of perfect competition. Instead, models with endogenous technological change embody alternative equilibrium concepts, typically either competitive equilibrium with externalities, or imperfect competition in which not all agents in the economy are price takers, but rather some agents have a degree of market power.[5] In these types of models, the equilibrium of the decentralized or "*laissez-faire*" economy will explicitly differ from the social optimum.

The new growth theory's implications for technological change and long run economic growth are in sharp contrast to those of the conventional model. In models with endogenous technological change, the market system will not necessarily result in an efficient or optimal production of knowledge, and government policies may indeed affect long run economic growth. In particular, in some endogenous growth models (including that of Romer), the decentralized economy will allocate insufficient resources to research and development, and government policies subsidizing R&D can increase long run welfare and economic growth by increasing the rate of technological development. This result is related to the long-standing finding that social rates-of-return[6] to research and development (R&D) exceed private rates of return, so that the government can — in principle — improve the performance of the economy by subsidizing R&D.[7] While some of the new models predict over-investment in R&D in the laissez-faire case, the most recent work confirms that, on the contrary, private investment in R&D is too low from the standpoint of economic efficiency. Jones and Williams (1998), applying new growth theory methods to study rates of return to R&D, estimate that the optimal share of GDP allocated to R&D in the U.S. economy would be from two to four times higher than the actual share. The implication of this finding, of course, is that in principle there are policies the government could introduce that would increase economy efficiency with respect to the level of R&D.

C. Endogenous Growth Theory and Energy-Efficiency Trends

With few exceptions, economic models applied to climate policy or integrated assessments have embodied the conventional treatment of technological change, deriving from the work of Solow.[8] In particular, modelers assume that increasing energy efficiency (or decreasing carbon intensity of energy-intensive goods or processes) results from factors that are exogenous to the workings of the economy. This is typically represented in models by some variation on what is known as "autonomous energy efficiency improvement" or AEEI. The level of AEEI determines the rate at which energy efficiency increases independent of any other factors represented in a given model. This rate, in turn, determines how quickly the economy moves to lower carbon outputs *without* policy intervention. Therefore it considerably influences how extensive — and expensive — carbon abatement policies must be to reach particular targets or to satisfy a cost-benefit criterion. It is well known that the magnitude of the AEEI (or its equivalent) indeed has a substantial impact on cost estimates of climate policy. This has resulted in a long running but inconclusive debate over the magnitude and interpretation of "autonomous" trends in energy efficiency.

To describe the potential implications of endogenous growth theory for climate policy modeling, it is useful first to consider what can happen, in principle, in models that incorporate the AEEI approach. Most such models are designed specifically to analyze the effects of carbon and/or energy price premiums. In a modeled scenario in which the government imposes such a price premium, energy sources that are relatively carbon-intensive will become more expensive relative to alternative sources, and consumers and firms will therefore substitute away from them. The result is a decrease in the economy's carbon output, at a cost determined by the details of the model.

At the same time, the autonomous trend in energy efficiency will continue its work, as it were, *unaffected by the carbon price*. This is after all the definition of "autonomous." The rate at which energy efficiency increases in the economy through any mechanism other than substitution will be unchanged. Thus, the model's predictions of both the effects and costs of a policy will be determined by the combination and interaction of substitution and exogenous trends.

Intuitively, this picture would seem to omit a critical element: the entrepreneurial response to the carbon price premium, in the form of increased efforts to invent and apply new forms of energy-efficient technologies and practices. That is, the carbon price premium would create new economic incentives for innovations in energy efficiency and carbon reduction in addition to the incentives for substituting away from carbon-based energy sources. Agents in the economy would recognize this new opportunity and respond accordingly; the result would be an increase in the *rate* of energy-efficient and/or carbon-reducing technological change. For example, more expensive energy (resulting from a carbon-price premium) would make energy-efficient electric motors more valuable to consumers and firms, since the cost of operating electric motors would increase. Recognizing this, engineers, inventors and others would seek to create such efficient motors. The same reasoning applies, in principle, to any technological application of energy. Overall, then, more expensive energy would accelerate the invention of energy-efficient technology across a range of applications. Thus, because new technological means of lowering energy consumption and carbon output would appear more quickly than in the absence of the price premium, the estimated cost of abating carbon would be lower than in the case of purely autonomous technological change. Because of this entrepreneurial effect, consumers' and firms' opportunities to reduce energy use without reducing their benefits from the services of energy-using equipment would have increased.

D. Applications to Climate Policy

The possiblity of an entrepreneurial response to a given climate policy has stimulated considerable interest in the implications of endogenous growth theory for climate modeling. Researchers have recognized that endogenous technological change could in principle enhance the effects of carbon-reducing policies. However, they have also raised the possibility that stimulating climate-related R&D might result in a diversion of resources that would slow down R&D elsewhere, or otherwise impose some additional cost to the economy. More specifically, the key input into R&D is human capital or human expertise — the knowledge and skills of scientists, engineers, and other highly trained individuals. Because this human capital is a scarce resource, diverting it into climate-related research could result in an economic loss associated with removing this capital from its other productive uses. This is referred to as the "crowding out" problem. For example, suppose that a carbon price premium were introduced and had the effect of drawing engineers or other "knowledge workers" away from a different industry to conducting research on energy efficiency. In this case, the climate might benefit but the other industry would suffer — technological change in it would slow down. As Kopp (1998) puts it, in general: "The redirection of R&D activity to incentives created by [GHG] abatement can be be expected to reduce the rate of technical advance in other activities and sectors."

Alternatively, new engineers could be trained to ensure that there was sufficient human capital to apply both to the invention of carbon or energy-reducing technology and to other kinds of research. In this case, however, the costs of the training itself would have to be borne somehow: an opportunity cost would result from diverting resources to such training and away from either consumption or investment elsewhere in the economy.

A frequently-cited example of this opportunity cost argument is presented by Nordhaus (1997), who extends his well-known Dynamic Integrated Climate Economy (DICE) model to incorporate endogenous technological change and to study its implications for the cost of carbon abatement. Nordhaus assumes that crowding out will have a high cost. As he puts it, "...higher inventive activity in the energy/climate sector is likely to lead to a decline in inventive activity in other sectors." Nordhaus argues that this would occur for one of two reasons:

- "[T]here is a fixed stock of human ingenuity...As some [inventors] are attracted to the energy/carbon sector to try to solve the world's problems, they will pay less attention to unsolved problems in other sectors. If John Von Neumann had been attracted to solving problems of molecular biology or the environment rather than mathematics, economics and computers, the cost to society would have been much more than one person-lifetime of Hungarian labor inputs."[9]

- "[I]ncreasing incentives in one sector will lower incentives in the other,"[10] thereby causing a decrease of output in the other sectors. That is, the opportunity cost would be present even if human capital were not in fixed supply.

Specifically, Nordhaus assumes a "supernormal" opportunity cost of $10 of lost output in other sectors per $1 of shifted R&D. As a consequence of this assumption, the crowding out of invention in other sectors offsets most of the carbon-reducing benefits of endogenous technological change. Thus Nordhaus finds that incorporating endogenous technological change has only a very small net effect on the costs and level of optimal carbon reductions.

This reasoning stands in contrast, however, to the basic logic of the new growth theory. To explain why, it is useful to refer to the model of Romer (1990), which is a key benchmark in this area. Romer's model represents an abstract economy consisting of three sectors: (1) a research sector that employs human capital to produce designs for products, (2) an intermediate goods sector that uses these designs to produce intermediate goods, and (3) a final output sector that combines human capital and the intermediate goods to produce a final commodity that can be consumed by households or re-invested in production. Overall human capital is in fixed supply.

Romer assumed that there are no costs of retraining or of other adjustments in moving human capital (i.e., skilled workers) from one sector to another. Although this is an idealization, it serves to focus attention on underlying long run factors rather than shorter-run adjustment phenomena.[11] The technical approach is that of analyzing the long run equilibrium or "steady state" of the economy. This is the ultimate equilibrium reached by the economy after transitional effects have subsided.[12] While this method does not allow for the study of important shorter-run effects of policy interventions, it is widely used in theoretical work — essentially for reasons of analytical tractability — to study the long run behavior of economies and the effects of policies.

Romer demonstrates that, in this model, the *laissez-faire* equilibrium allocates too little human capital to research. The source of this inefficiency is, as discussed in the previous section, the public good characteristic of the technological knowledge that is the product of R&D. Because of this characteristic, private incentives do not result in an economically optimal supply of R&D: in this model, an insufficient number of knowledge workers engage in research. Under these conditions, a subsidy to R&D causes human capital to move into research from its other uses. But although there is thus crowding out in the narrow sense described above, this shift of human capital results in an increase in economic efficiency: a correction of a market imperfection arising from the characteristics of knowledge as a commodity. In contrast to Nordhaus' analysis, in this model the opportunity costs of moving human capital into R&D are necessarily exceeded by the benefits.[13]

Romer's analysis, however, does not deal with the problem of R&D on carbon abatement specifically, nor does it address the problem of competing forms of R&D. Both are studied by Goulder and Schneider (1999), who conduct a more detailed analysis of the opportunity cost problem using a form of endogenous, carbon-reducing technological change, both analytically and with a computable (that is, numerical) general equilibrium model.[14] Their models distinguish conventional from "alternative" (i.e., low-carbon) energy production, and allow for technological change in both sectors. In Goulder's and Schneider's model, endogenous technological change is represented by knowledge "spillovers": new knowledge is produced using conventional inputs and production technology in one industry, but can be freely used by any other industry.[15]

Goulder and Schneider study the effects of carbon taxes within this structure, and reach two key conclusions. First, incorporating endogenous technological change lowers the estimated cost of meeting a particular carbon output target, relative to a scenario in which technological change is purely autonomous. This is consistent with intuition, since the carbon-abating effect of price-induced technological change complements both substitution and underlying autonomous trends. Second, in a cost-benefit analysis, endogenous technological change increases both the gross costs and the net benefits of a carbon price premium. Costs increase because including the additional, endogenous effect makes the economy more responsive to the price premium than it otherwise would be. Thus, the economic change resulting from the carbon tax prior to accounting for the environmental improvement — which determines the gross cost — is greater with endogenous technical change. At the same time, net benefits increase because this effect increases the rate and level of carbon abatement, so that the resulting environmental improvement — which determines the benefit — is also greater.[16]

Goulder and Schneider's analysis emphasizes that producing new knowledge is not a "free" activity but rather requires resources like any other form of production. Thus, just as in Romer's model, the extent of pre-existing market inefficiencies bears importantly on the results. In particular, as discussed above, if the *laissez-faire* economy does not produce an optimal level of R&D, there is an underlying inefficiency in the market that can be ameliorated by policy. In the Goulder and Schneider model, a pre-existing under-investment in energy saving R&D *relative to other kinds*[17] of R&D serves to strengthen their conclusions regarding the gross cost-reducing and net-benefit-increasing effects of endogenous technological change. The reason is again that the key input into research — human capital or expertise — is a scarce commodity, and reallocating it to climate-relevant research will, in their model, entail a reduction in technological change in other sectors. When human capital is initially underallocated to carbon-reducing R&D, however, the costs of crowding out are mitigated.

To gain further insight into the crowding out problem in particular, Sanstad (1999) studied how a research subsidy targeted to a particular industry would affect the overall allocation of human capital when there are two forms of R&D. Sanstad's approach was to extend Romer's 1990 model, discussed above, to represent two industries in which both research and production occur; each industry is structured exactly as the overall economy is in Romer's model. The industries compete for human capital, which serves as the primary input in both research and production in each industry. Overall human capital is again in fixed supply. Research in each industry serves as an input to production only in that industry; that is, there are no knowledge spillovers between the industries. As in the basic Romer model, the decentralized or *laissez-faire* equilibrium is characterized by an under-allocation of human capital to research in both industries. This is due to monopoly pricing[18] and the non-rivalry and partial non-excludability of the outputs of research.[19]

Sanstad's model does not address the indirect effects of carbon prices on technological change, but rather focuses on the direct effects of a government subsidy to research in one of the industries (financed by lump-sum taxation[20]). Specifically, it is formulated to analyze how such a subsidy changes the allocation of human capital among both industries and both types of activities (research and manufacturing). As in Romer's model, the approach is to focus on the steady state.

The targeted research subsidy, as expected, shifts human capital from production to research in the subsidized sector. Rather than crowding out human capital from the other research sector, however, it also has the effect of *increasing* human capital in the competing research sector in the long run. The reason for this effect is two-fold. First, in analogy with standard models with exogenous technological change, rates of technological progress equalize across sectors in the steady state. (This is part of the definition of "steady state.") Second, in this formulation, the fact that the production of knowledge through research is modeled as a productive activity that employs human capital as an input means that human capital adjusts to achieve the rate of technical change that characterizes the steady state. (This rate is determined by the parameters and structure of the model.) The research subsidy draws human capital into the subsidized R&D sector, thereby increasing the long run rate of technological change arising from that sector's output of product designs. This new rate of change then becomes the benchmark rate for the overall growth of the economy in the new steady state. Thus, the rate of change in the "competing" R&D sector also increases to match the economy-wide steady state rate.

To illustrate this effect, imagine two industries: refrigeration and video games. If the government were to subsidize R&D for efficient refrigerators, but not for new kinds of video games, then in Sanstad's model, the rate of technical change in the video game industry would also increase in the long run. Human capital would be moved by the subsidy out of refrigerator manufacturing and into both refrigeration and video game R&D.[21] Because, in this model, there is initially an over-allocation of human capital to video game manufacturing, the shift would improve economic efficiency.

What do these various findings tell us about the crowding out problem? First, with a fixed supply of human capital, there is no doubt that increasing human capital in one sector necessarily means there will be less available to some other sector.[22] The question, however, is what conclusions one can draw about: (1) the costs of this diversion, and (2) its effects on technological change in other sectors and on overall economic efficiency. The work just summarized indicates that subsidizing R&D in one sector need not crowd out R&D in others. Even when it does, however, as in the Goulder and Schneider model, the presence of endogenous technological change will still affect estimates of the costs of carbon-abatement. In particular, it will both lower the cost of meeting a given carbon reduction target, and increase the net benefits of a carbon price premium.

Goulder and Schneider argue that, if there is economy-wide under-investment in R&D, then the policy response should be a general subsidy to R&D rather than a targeted subsidy to a particular sector such as energy-efficiency research. Suppose, then, that the market undersupplies both climate-related and other forms of R&D, and that the government introduces both a general R&D subsidy and a carbon price premium. Then R&D on all topics, including carbon reduction, will increase, and there will also be a substitution away from carbon-intensive energy sources. Both effects will enhance economic efficiency because both involve the correction of a market imperfection, in one case the undersupply of knowledge, in the other the oversupply of carbon emissions. Thus, in this case also, the existence of market imperfections related to technological innovation implies that the costs of crowding out will be mitigated.

Overall, these results also demonstrate the fundamental importance of better understanding the nature and severity of pre-existing distortions relating to R&D in the economy. As in its other applications, the empirical and policy significance of new growth theory applied to climate policy rests fundamentally on the degree to which the economy does or does not undersupply R&D in the absence of policy. This is a very difficult problem due to data limitations and measurement issues, but nevertheless is clearly a key priority for future work.

E. Summary and Conclusions

Climate policy modelers have with few exceptions represented technological change as an exogenous or autonomous process not subject to market forces. As a consequence, these models rule out by assumption the possibility that economic policies to abate carbon could also stimulate carbon-reducing or energy-saving technical innovation. Market-based innovation and the entrepreneurial pursuit of technological progress, however, are not only clearly endogenous economic processes but indeed are hallmarks of modern advanced economies. It is therefore ironic — and a potentially significant shortcoming — that such innovation has not been represented adequately in the bulk of research on the economics of climate policy.

In the past several years, a number of researchers have begun to investigate the technical details of incorporating endogenous technological change into climate policy modeling, and the policy implications of this enhancement. One theme that they have emphasized is that, while a carbon price premium might indeed draw entrepreneurial efforts to developing climate-friendly technology, this effect would be offset by the resulting "crowding out" of technical expertise — "human capital" — from its other applications. The opportunity cost of drawing technical experts away from non-climate-related R&D would reduce the benefits that would accrue from accelerating research on climate protection.

This conclusion, however, rests in turn on certain assumptions regarding the nature of technological knowledge as an economic commodity and the effectiveness of the market system in supplying it. Many empirical studies have repeatedly found that social returns to R&D exceed private returns, implying that policies to promote R&D are economically justified. More recently, the "new growth theory" has developed a sophisticated theoretical apparatus that allows for rigorously modeling endogenous technological change. This new work explicates how and why the market economy can be expected to under-supply R&D in the absence of policy.[23] The work described in this paper expands on this theme by showing why, from the perspective of the new growth theory, shifting human capital into climate-related R&D need not result in offsetting opportunity costs if this "capital" is drawn from applications to which such capital has been over-allocated.

This finding indicates that the fundamental issue underlying endogenous technological change in climate policy is the extent of pre-existing distortions in the market for carbon-reducing R&D. This research problem is of great difficulty due primarily to measurement and data issues. Nonetheless, it is clear that the opportunity cost argument described above should not be taken as the final word on endogenous technological change and climate policy. This finding should renew attention to the possibility that, by omitting the "entrepreneurial effect," current models may be systematically overestimating the costs of carbon abatement policies.

Endnotes

1. This work was conducted while the author was a visiting scholar at the Energy and Resources Group, University of California at Berkeley.

2. Governments may cap the total amount of emissions, distribute or sell emission “permits” or “allowances,” and let the market determine the price and distribution of these allowances. Since a cap would essentially restrict the supply of carbon-based fuels, GHG consumers would bid up the price until demand equaled supply.

3. The research discussed in this paper primarily involves models designed to analyze carbon and/or energy taxes rather than tradable permit systems. Nonetheless, the same general conclusions apply to permit systems. The phrase “carbon price premium” is used as a shorthand to refer to both kinds of policies.

4. It is important to note that patents on inventions or designs do not change this reasoning. Patents are a form of property rights — that is, they impose at least partial excludability. They do not affect non-rivalry.

5. “Equilibrium” is simply the set of prices and quantities that equate supply with demand in all markets.

6. Rates of return here are simply the payoffs over time — either to society or to private agents — of investments in R&D.

7. See, for example, Foster Associates (1978), Mansfield et al. (1977a, 1977b), and Nathan Associates (1978). This older literature on social and private rates of return to R&D has a narrower focus than that of the new growth theory and did not deal with the theoretical underpinnings or underlying sources of the social vs. private “gap.”

8. The most noted exception to this rule is the Dynamic General Equilibrium Model (DGEM) of Jorgenson and Wilcoxen (1990). Technological change in DGEM is not fully autonomous in the sense described here, but rather responds to changes in relative factor prices, a specification known as “factor price bias.” Technically, DGEM lies between the standard models and the endogenous growth framework, in that it allows for non-autonomous technological change in this sense while still assuming perfect competition, as in the standard models, and not explicitly modeling technical innovation as the outcome of optimizing behavior of agents in the economy.

9. Nordhaus (1997). pp. 8-9. John von Neumann was a Hungarian-born genius of the mid-twentieth century who was one of the founders of computer science and of the modern economic theory of general equilibrium as well as a key figure in the development of thermonuclear weapons.

10. Nordhaus (1997), p. 8.

11. Note that Goulder and Schneider do assume that there are costs of adjustment. These costs tend to offset any benefits that accrue from re-allocating human capital, but do not negate them.

12. This long run equilibrium is also known as the economy’s “balanced growth path.” The idea of the steady state (or balanced growth path) can be visualized by using the analogy of a rocket launched to visit another planet. In taking off and reaching orbit, numerous adjustments may have to be made to keep the rocket on course. Thereafter, it will settle into its final trajectory. This trajectory is the analogue to the long-term path, or steady state, of the economy.

13. An alternative but complementary explanation of Nordhaus' results is suggested by Goulder and Mathai (2000), who note that the estimated impact of endogenous technological change on optimal abatement policy is extremely sensitive to what is assumed about the details of the marginal abatement cost function. Relating this factor to those discussed in this paper is a subject for further research.

14. A computable general equilibrium model is a numerical representation of an entire economy, with rational behavior (utility and profit maximization, and price-taking) on the part of consumers and firms, and supply equaling demand in all markets.

15. Technically, Goulder and Schneider apply the equilibrium concept underlying Romer's first (1986) model, that of competitive equilibrium with externalities. In this approach, a decentralized equilibrium is possible because the increasing returns associated with the production of R&D are assumed to be completely external to individual firms.

16. This assumes that the carbon tax itself meets a cost-benefit criterion.

17. There may be under-investment in energy saving R&D relative to other forms of R&D because of both underlying economic differences and different pre-existing policies. That is, a general under-investment in R&D does not mean that every specific R&D sector is affected to the same degree. Also, there may be prior differences among, e.g., government subsidies to different kinds of R&D.

18. Monopoly pricing contributes to under-allocation of human capital to research because it implies that inventors are not fully compensated for the value of their inventions.

19. Romer's 1990 or "second" model, applied by Sanstad, incorporates a form of imperfect competition to model the deviation from perfect competition that is implied by the new assumptions on technological change. This is regarded as its key technical innovation, and has formed the basis for most subsequent work in the area.

20. A lump-sum tax is one that only affects consumers' income and does not induce any substitution of one commodity for another on the part of consumers. A lump-sum tax is a commonly used theoretical benchmark; it is close to impossible in practice to design lump-sum taxes.

21. This finding — like many findings of dynamic economic analysis — clearly relies heavily on the steady state focus. It should be noted, however, that essentially all dynamic models of this type — both theoretical and computable, and with endogenous or exogenous technological change — are based in part on the assumption of a steady state; this is true even when transitional effects are also included in the analysis. Aghion and Howitt (1999, p. 9) justify the use of the steady state assumption in endogenous growth models by noting that "...because innovations often have effects that take decades to work out, we are primarily interested in 'the long run,' and the steady state is a convenient analytical device for modeling the long run-for distinguishing between effects that last and effects that are transient." In the present case, the increase in human capital in the competing R&D sector might or might not appear immediately were transitional dynamics to be taken into account, but it would appear eventually. It may be that gaining further insight into the underlying phenomenon will require modeling advances that relax or generalize the steady state assumption; this is a topic at the frontiers of current research. (See, for example, Kongsamut et al. [1998]; Eicher and Turnovsky [1998])

22. However, the supply of human capital need not be fixed, especially in the long term, because both individuals and society can invest in its production through education and training.

23. As discussed above, this undersupply can take the form of too much human capital supplied to some forms of R&D and too little to others, an overall undersupply of human capital able to perform R&D, or both.

References

Eicher, T.S. and S.J. Turnovsky. 1998. “Non-scale Models of Economic Growth.” Working paper, Department of Economics, University of Washington, February.

Foster Associates. 1978. A Survey of Net Rates of Return on Innovation. Report to the National Science Foundation, May.

Goulder, L.H. and S.H. Schneider. 1999. “Induced Technological Change and the Attractiveness of CO2 Abatement Policies.” *Resource and Energy Economics* 21 (3-4) (August): 211-253.

Goulder, L.H. and K. Mathai. 2000. “Optimal CO_2 Abatement in the Presence of Induced Technological Change.” *Journal of Environmental Economics and Management* 39: 1-38.

Jones, C.I. And J.C. Williams. 1998. “Measuring the Social Return to R&D.” *Quarterly Journal of Economics* 113 (4) (November): 1119-1135.

Jorgenson, D.W. and P.J. Wilcoxen. 1990. “Intertemporal General Equilibrium Modeling of United States Environmental Regulation.” *Journal of Policy Modeling* 12 (4) (Winter): 715-744.

Kongsamut, P., S. Rebelo, and D. Xie. 1998. “”Beyond Balanced “Growth.” Working paper, University of Rochester, Northwestern University, National Bureau of Economic Research, Hong Kong University of Science and Technology, April.

Kopp, R.J. 1998. “Climate Policy and the Economics of Technical Advance: Drawing on Inventive Activity.” Climate Issue Brief #8, Resources for the Future, January.

Lucas, R.E., Jr. 1988. “On the Mechanics of Economic Development.” *Journal of Monetary Economics* 22 (July): 3-42.

Mansfield, E., F. Husic, J. Rapoport, A. Romeo, E. Villani, and S. Wagner. 1977a. *The Production and Application of New Industrial Technology*. New York, W. W. Norton.

Mansfield, E., J. Rapoport, A. Romeo, S. Wagner, and G. Beardsley. 1977b. “Social and Private Rates of Return from Industrial Innovations.” *Quarterly Journal of Economics* XCI (May): 221-240.

Nathan Associates. 1978. Net Rates of Return on Innovations. Report to the National Science Foundation, July.

Nordhaus, W.D. 1997. “Modeling Induced Innovation in Climate-Change Policy.” Working paper, Department of Economics, Yale University.

Romer, P.M. 1986. “Increasing Returns and long run Growth.” *Journal of Political Economy* 94 (October): 1002-1037.

Romer, P.M. 1990. “Endogenous Technological Change.” *Journal of Political Economy* 98, pt 2: S71-S102.

Sanstad, A.H. 1999. “Endogenous Technological Change and the Crowding Out Problem in Climate Policy.” Paper presented at the Conference on Economics and Integrated Assessment, Pew Center on Global Climate Change, Washington, DC, July 21-22.

Solow, R.M. 1957. “Technical Change and the Aggregate Production Function.” *Review of Economics and Statistics* 39 (August): 312-320.

III. The Organizational Structure of Firms and Economic Models of Climate Policy

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A. Introduction

Standard economic models of climate policy[1] *do not offer a realistic portrayal of the behavior of the private sector business organizations that actually produce most goods and services.* It may perhaps be surprising to non-specialists that the way production is represented in IAMs does not correspond to the modern theory of the firm, yet that is the case. Conventional energy/economic models (of the type used to project future energy demand and supply, the consequences of implementation of the Kyoto Protocol, or the economic effects of a carbon tax, for example) typically rest on two abstractions in describing firms. *Technology* is represented by a production function, a mathematical relationship between conventional inputs or "factors of production" (labor, capital, and sometimes materials and energy) and output.[2] *Behavior* is characterized by profit maximization or an equivalent optimization rule.

These mathematical abstractions have a long history of successful application in economics. They have proven useful for analyzing issues such as the distribution of income between the various factors of production and the determinants of the prices of goods traded in well-functioning markets. They are, however, inadequate for examining the internal workings of modern business firms, particularly in the context of the market and non-market changes that would accompany the transition to a policy regime seriously addressing the climate problem.

The conventional models fall short in their representation of the productive sectors of the economy in four important ways:

- They assume that a firm has a single objective, the maximization of profits, whereas in reality a firm may have multiple objectives, including improving financial performance, increasing market share, maintaining good customer relations, conforming to the values and motivations of the firms' employees, and achieving "communal" goals such as preservation of environmental quality;

- They assume that a firm maximizes profits by choosing how much of each of its "factors of production" (i.e., labor, capital, materials, and energy) to employ, even though very little of business managers' time and attention is really devoted to such decisions;

- They assume that technical change occurs independent of the activity of firms, despite the fact that it actually depends on complex business decisions involving the acquisition and dissemination of information and technologies; and

- They assume that all firms are already behaving optimally, although in practice there is almost always room for improvement in economic performance.

This chapter will show that these mischaracterizations lead to misunderstanding of the activity of firms, which in turn results in unreliable and biased model forecasts of the costs of GHG reduction policies. The consequence is a gap between most formal economic analyses of climate issues and the practical, on-the-ground efforts of business organizations to act in ways that simultaneously are socially responsible and consistent with the interests of corporate shareholders. By adhering to a model of production that does not correspond to the best current theories of organizational behavior, conventional IAMs are limited in their capacity to provide guidance to policy-makers in business and government.

B. The Representation of Production in Climate/Economic Forecasting Models

Maximization of profits (subject to a production function embodying the technology available to the firm) is mathematically tractable and lends itself to expression in equations that can easily be embedded in a larger model of the macro-economy; this simplification, however, does not fully capture the real-world activity of firms. Conventional models shed little light on the incentives or motivations of the individual agents who make up the firm, or on the choices about organizational structure, relations with customers and suppliers, and strategic planning that lie at the heart of business management. As Coase (1937) recognized long ago, the conventional theory does not even give an explanation of why firms should exist at all, instead of a world in which all economic transactions are mediated through markets alone. At the most basic level, very little of what managers do involves choosing the quantities of the conventional factors of production that constitutes the decision problem in the production function representation of the firm. Rather, managers spend most of their time supervising their employees, collecting and processing information, engaging in intra-firm politics and bureaucratic maneuvering, and communicating with the outside world. Many firms are linked to customers and suppliers and focus on managing a production process that depends on these external relationships (which, in turn, involve more than simple market transactions).

The production function representation has been augmented and modified in fundamental ways by the modern theory of the firm. For example, the "new institutional economists" such as Oliver Williamson (1985, 1998; see also the 1988 review article by Alchian and Woodward) emphasize the importance of minimizing transactions costs (including the internal costs of operating and maintaining the firm) and controlling opportunism (the tendency for agents outside the control of the firm — such as suppliers or contractors — to use their temporary or localized market power to try to take advantage of the firm). In addition, it has been understood since at least the time of Berle and Means (1932)[3] that the incentives faced by owners and managers, and by managers at different levels or in different segments of an organization, are not necessarily compatible. This "principal/agent problem" is another central concern of the modern theory of the firm.

These are not the only problems with the old-fashioned model of production, however. Herbert Simon[4] and those who have taken up his insights realize that the conventional profit maximization assumptions also fail because of cognitive or computational difficulties faced by firms and the agents within them. These information-processing limitations are usually referred to as "bounded rationality," and their existence has strong implications for both the theory of the firm and the representation of the firm in climate/economy models.[5] It is worth noting in this regard that the social science disciplines other than economics have never adopted the optimization framework as a universal standard. The models of sociologists, social psychologists, management scientists, and others have often paid attention to the determinants of organizational performance, and to the interactions between the capabilities of the agents, the structures of their organizations, and the nature of the tasks being performed,[6] but optimization models have not often been the chosen vehicles for representation of these processes.

Modern business history also has gone beyond the production function/profit maximization representation of firms. As Raff and Temin (1991) put it:

> Business history is about firms, and there is not much to traditional economic theory's firms or to the problems they confront. The structure of the wants of the consuming public is given [in conventional theory]. So is the particular selection of those wants that any particular firm should try to meet. So also are the methods by which inputs are to be combined to produce those goods. Nor are there any difficulties involved in getting the inputs to combine as they are meant to. Most firms are small with respect to the markets they trade in, and there are no intricate reactions or interactions between buyers, sellers, or buyers and sellers to be puzzled out or manipulated. Altogether, strategic choice (in both the businessman's sense and that of the game theorist) is absent, and the details of organization are never a problem (p. 7, footnote and references omitted).

Business historians are interested in specifics, and are not committed to a particular theoretical perspective in analyzing the development of firms. This empirical orientation necessarily creates some distance from any kind of generic abstraction of firms' behavior or processes.

Regardless of how useful the production function/profit maximization representation of firms may be for some applications, its uncritical incorporation into IAMs for climate policy analysis is not an innocuous simplification. The very elements of business response to climate policy that are most critical — the determinants of the pace and direction of technological change (including both innovation and diffusion), and the ways in which "non-economic" values are translated into corporate policy and action — are elements that cannot easily be treated within the conventional production framework.[7] The conventional models assume that technological innovation and the diffusion of new technology occur independent of the activity of firms, while in reality these processes depend on complex business decisions (e.g., about research and development expenditures, or the adoption of possibly superior but potentially risky new technologies).

To make the nature of the problem more concrete, consider the assumption, implicit in conventional models, that firms and other productive entities are located on their "production possibility frontiers."[8] Drawing the production-possibility frontier of a firm is equivalent to specifying a production function such that a given set of inputs is transformed into a unique set of outputs. The production function represents technology, and the technology that is assumed to be available determines the extent to which trade-offs must be made among outputs. A standard representation of the production-possibilities frontier is shown in Figure 1a. Only two goods (ordinary output and environmental quality)[9] are portrayed, but the discussion generalizes easily to multiple outputs. Optimization or profit maximization by the firm guarantees that production will occur on the frontier, at initial point I_a, for example. If the firm initially is at point I_a in Figure 1a, the only way it can produce a higher level of environmental quality (lower emissions), such as point *J*, is by moving *along* the production-possibilities frontier and reducing its output of ordinary goods.

There are two situations in which this "inevitable trade-off" fails to describe the actual situation faced by the firm. These are shown in Figures 1b and 1c.[10] Figure 1b indicates that the firm's starting point I_b is *inside* the production-possibilities frontier. (Conventional theory says this could not happen because a firm inside its frontier is not fully optimized.) In this case, any movement into the region in the northeast quadrant above point I_b represents an improvement in both the production of ordinary output and the production of environmental quality. An example of a firm starting at point I_b in Figure 1b would be the case of a firm that has not made investments in energy efficiency having a rate of return greater than other profitable investment opportunities of equal risk. Such situations have been documented extensively in the real world.[11] Their existence constitutes empirical confirmation of the location of some firms inside their production-possibility frontiers. Figure 1c shows a different way this simultaneous improvement in economic and environmental performance could take place. Here, the firm begins on its production-possibilities frontier at point I_c, but now *technological progress* expands the frontier from P_0P_0 to P_1P_1. If the firm moves from I_c towards the new frontier, it is again possible for its performance to improve in both dimensions.

In addition to the "bottom-up" studies cited in Endnote 11, numerous case studies have found the same kind of multiple benefits from technological progress in environmental protection. For example, in

Figure 1

Alternative Potential Trade-offs between Ordinary Goods and Environmental Quality

Figure 1a – Conventional Trade-off

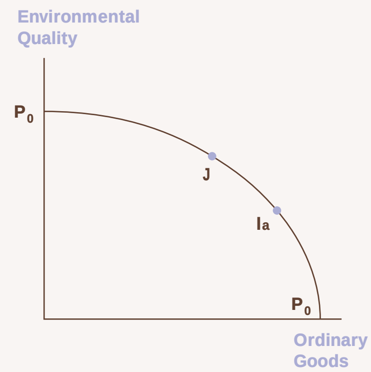


Figure 1b – Production Inside the Frontier

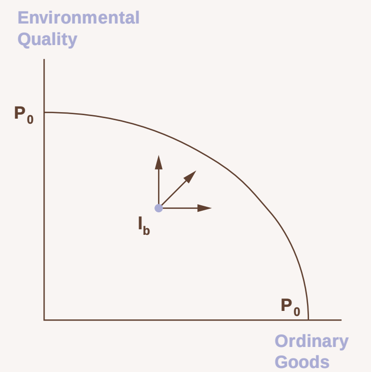
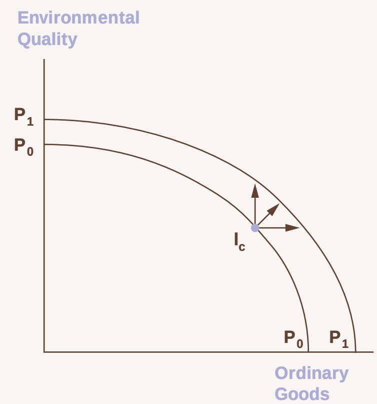


Figure 1c – Production with Technological Progress



response to the Montreal Protocol on Substances that Deplete the Ozone Layer, companies invented new methods for producing electronic equipment without using ozone-depleting cleaning solvents. This resulted in lower costs without reductions in product quality (Economic Options Committee [1994]). According to one study of this transition:

> Many companies with successful ODS [ozone depleting substance] phase out programs developed new cleaning methods, or eliminated the need to clean altogether, while maintaining their competitive edge. Electronics companies report cost savings, simplified manufacturing, and higher reliability by switching to new technologies. For example, Ford, Honeywell, Hughes, Motorola, and Texas Instruments are now manufacturing printed circuit boards that are cleaner than boards produced with CFCs, and meet the most demanding military specifications (Andersen and Zoi [1993]).

The benefits that flowed from this advance in environmental technology extended across several dimensions of business performance:

> The fact that firms saved money by adopting "no clean" methods that avoid the use of solvents cannot be underestimated, but participating corporations reaped a great deal more indirectly. The corporations saved by pooling research and development resources....Eliminating CFCs enhanced the credibility of corporate environment departments, often boosting support for other cost-saving environmental goals, such as waste reduction. And firms that took leadership roles reaped immense public relations benefits, domestically and abroad. However hard to quantify, improved employee morale, higher quality production, and enhanced relationships with regulators and environmental groups certainly boost bottom lines (Wexler [1996] p. 92).

The same kind of direct and indirect economic benefits have been found repeatedly in case studies of energy efficiency and other types of waste-reduction investments (Romm [1994, 1999]; von Weitzsäcker et al. [1997]; Hawken et al. [1999]).

The consequences of portraying the firm as operating on a static production-possibilities frontier are serious:

First, a mischaracterization of the full range of options (organizational, contractual, technological, etc.) available to firms will lead to *biased estimates of the cost of action to reduce pollution*. In particular, the estimates of the cost will be too high, because no reductions in pollution will appear possible without a cutback in activities that yield ordinary profit.

Second, mischaracterization of the production process *adversely influences the design of policies that might reduce pollution*. If the model is set up to include only commodity-like factors of production, and if the firm is imagined to be maximizing its profit subject to a production function that includes only these inputs, then the only policies that can reduce emissions are those that skew the input choices and make production less efficient given the technology. Such a view rules out a *priori* the efficacy of policies such as voluntary initiatives by firms to reduce their emissions, the effects of changes in corporate culture on the behavior of the firms, or the possible beneficial consequences of "benchmarking" of a firm's practices against other firms' environmental achievements.

Finally, the standard approach *misdirects the search for insight into the process of corporate change*. Exclusive adherence to an oversimplified representation of production will foreclose learning lessons from the modern theory of the firm as developed within the disciplines of economics, management science, and organization theory, as well as from the accumulated knowledge of business practitioners themselves.

These are one set of the problems that characterize the conventional models as they are applied to climate policy analysis, and recognizing them provides a strong justification for seeking to improve how firms are represented in such studies.

C. A Network Model of the Firm

Closer correspondence between up-to-date theories of the firm and IAMs would result in more reliable analysis of the effects of climate policies. At the present stage of knowledge, however, there is no single model of organizational behavior that commands universal assent, so some experimentation and exploratory work with different organizational models (emphasizing principal/agent problems, bounded rationality, etc.) is in order. One of the most promising avenues of investigation is to consider explicitly the consequences of the *network structure* of organizations. An intrinsic feature of all productive organizations is that they embody a set of channels of communication and authority that mediate all the significant decisions and activities of the organization. Any effort to improve corporate performance must take account of the structures of communication and control. A realistic representation of the decision-making process must recognize that in a large organization all the members are subject to reporting channels (including informal ones), acquire information from diverse sources, and have varying responsibilities depending on their place in the organizational hierarchy.

An immediate consequence of incorporating network structure into the model of the organization is that the problem of performance enhancement becomes quite complex. The number of potential organizational network structures grows very rapidly with the size of the organization, so that an exhaustive search for the "best" structure over all possible organizational forms would be unrealistically time-consuming. The complexity of finding optimized organizational structures means that in the real world the search for improvements in structure must make use of heuristics (i.e., search techniques) and rules of thumb, or rely on evolutionary selection mechanisms (such as survival of the more profitable firms and the failure of the less fit ones), to produce improvements. These are just the kinds of processes that characterize "bounded rationality" as that term has come to be understood. The trial-and-error nature of the search for improvements means that not all outcomes will be ideal.

A model illustrating these ideas has been developed by DeCanio et al. (1999). A stylized organization performs only two tasks, and performance on each task is contingent on the firm's network structure. The first task corresponds to the adoption of a profitable innovation by agents in the firm.[12] An example of this type of task is investment in energy-saving technologies having a high rate of return, such as efficient lighting, variable speed motors, or appropriate cogeneration of heat and power.[13] The adoption task can be thought of as one type of improvement in a firm's environmental performance. The network structure of the firm matters for the adoption task. While profitable innovations can be initially adopted anywhere in the organization, agents or units making up the firm adopt it subsequently only if they are in communication with others in the organization who have already adopted. The second task is a stylized version of production by assembly.[14] This task consists of collection by a "central agent" of information that initially is distributed throughout the organization. It is an abstraction of the activities that are involved in assembling a variety of primary inputs and intermediate goods into a final output, as in the case of production of finished commodities, or of reports, business plans, or other forms of non-commodity output.

In both cases, the time it takes for the innovation to diffuse through the organization or for the central agent to collect the production information is determined by the network structure of the connections between the agents. The faster the diffusion or collection, the greater the monetary return realized by the organization as a whole. However, maintaining the communications infrastructure entails a cost, and this cost increases with the "thickness" of network connections. Thus, there is a tension between denser connectivity (which speeds the diffusion and collection of information) and sparser connectivity (which costs less to maintain). The result of these opposing pressures is that the organizational structure chosen or evolved by the firm will depend on the parameters of cost and reward.

Finding the *optimal* organizational structure is quite difficult, even in this stripped-down model setting. It is unlikely that any simple formula or rule can pick out the best structure in all cases. However, by mimicking the processes that characterize biological evolution (i.e., mutation, reproductive exchange of information, and differential selection according to fitness), one can develop methods to search for model organizations that perform well in computer simulations. The technical details of the search mechanism and simulations are provided in DeCanio et al. (1999). Only the substance of the results will be described below.

The most striking finding to emerge from the simulation experiments is that for any particular set of cost and reward parameters, different organizational structures with roughly equivalent profitability may have quite different characteristics in their performance of the individual tasks. In particular, it is possible for different well-adapted organizations to have about the same profitability, but for some of them to perform better than others with respect to environmental impact.[15] Thus *improved environmental performance does not have to be purchased at the expense of profitability or productivity*. Once the complexities of organizational structure are taken into account, mutual reinforcement between economic and environmental performance is not necessarily in conflict with basic economic principles. This result is a version of the Porter Hypothesis (Porter [1991]; Porter and van der Linde [1995a,b]), that environmental protection and economic productivity can be complementary. This hypothesis is quite controversial from a conventional neoclassical perspective (see, for example, Palmer et al. [1995]).

Other results are significant as well. *Full optimization is difficult to achieve*, even for very small organizations performing the simplified tasks of the model. Standard search algorithms often find local optima that are distinct from the globally optimal structure. In other words, search procedures that work by making incremental improvements can get "stuck" at a solution that is better than nearby points, but inferior to what might be found if the scope of the search could be expanded to explore a larger region. The model optimization problem is much less complicated than the problems faced by actual firms. Yet real organizations have to employ *some* kind of search procedure in seeking to improve their performance, and the model results suggest that those search algorithms are likely to be imperfect. The search can only be conducted over a narrow range of all the possible situations, so that one cannot really know if a global optimum has been found. Furthermore, search procedures typically depend on their starting point, so that accidental or historical circumstances can influence the outcome. Thus, there is no reason to expect that the search methods employed by firms in the real world will routinely be able to find the optimal structural configuration. This suggests that a failure of optimization is the normal state of affairs.

D. A New Perspective on Organizations and Environmental Protection

The old-fashioned economic framing of the problem of environmental protection is one that emphasizes trade-offs, costs, and a conflict between strong financial performance and environmental stewardship. The consequence of this approach in IAMs has been to create an unexamined bias in thinking about how the climate change problem might be addressed. By getting "inside the black box" and examining how organizational structure can influence the behavior and performance of the firm, one can see that the relationship between economic and environmental performance is more complex than it usually has been portrayed.

It is possible to go beyond the formal model results to explore what they may imply for the practical question of how companies would be affected by policy initiatives to reduce GHG emissions. For example, the government might require emitters of GHGs to pay for their right to emit. This could take the form of a carbon tax (with non-carbon GHG emissions taxed proportionally to their global warming potentials), a cap-and-trade system with some kind of initial allocation or auction of emissions permits, or some blend of mechanisms. The prediction of conventional models would be that such a system would impose costs on the economy because of the trade-off between reducing carbon emissions (which had previously been free inputs to the production process) and the economic goals of firms.[16] A picture of the interaction between corporate economic and environmental goals corresponding to the ordinary assumptions is displayed in Figure 2. In this diagram, economic and environmental performance are opposed to each other, and the conventionally assumed trade-off between them produces incompatibility among management priorities.

In contrast, the model described in Section C suggests a different relationship between the ordinary economic goals of the firm and its environmental goals. In the network model, the infrastructure of the organization supports the full range of its activities, from generating sales revenue (through accomplishment of the production task as expeditiously as possible) to adoption of environmentally friendly technologies. These complementary tasks give rise to the kind of relationship between economic and environmental performance that is shown schematically in Figure 3. In this view, the environmental objectives of the firm are intrinsic to overall operations rather than being an "add-on" that soaks up scarce resources. Internal organization and managerial perspectives are such that the institutional changes and technological innovations that contribute to the bottom line also support enhanced environmental performance.

Organizational infrastructure, internal culture, and the incentives/motivations of employees are aligned, and all can strengthen the activity of the firm along multiple dimensions. Such a positive outcome is not guaranteed, of course — the task of management would be far simpler than it is if it were easy to coordinate the firm's many objectives. Some kinds of environmental clean-up activities will still add to the costs of production, because the real costs of waste disposal have to be accounted for. The underlying point, however, is that a more integrated approach to the joint activities of the firm (including meeting environmental objectives) may provide opportunities for productivity gains through process redesign, structural reorganization, and mobilization of latent possibilities for innovation within the firm.

Figure 2

Conventional View of Conflicting Goals

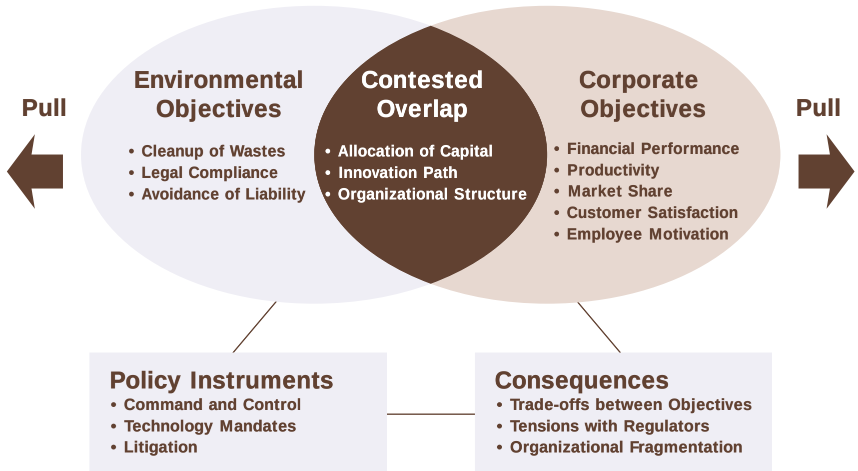
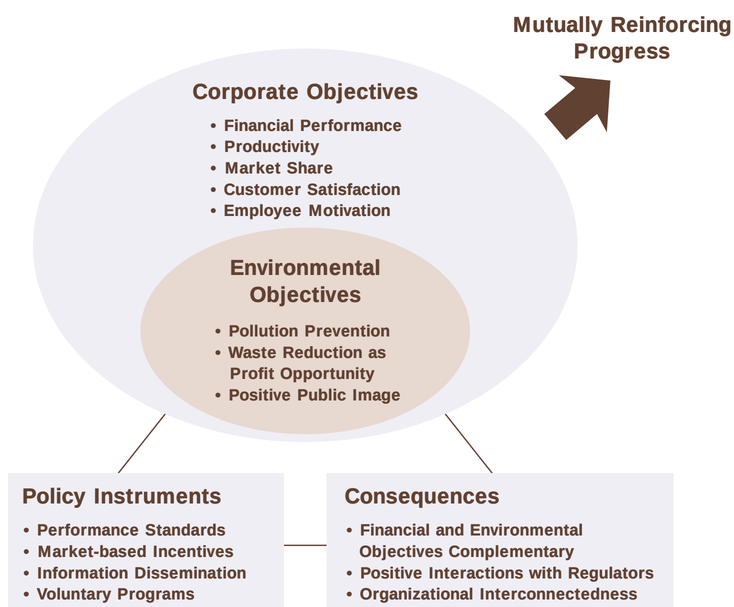


Figure 3

Integrated Approach to Environmental/Economic Goals



E. Conclusions

This chapter has shown how conventional economic models do not adequately represent the behavior of firms, leading to misunderstanding about how firms innovate, and to the presumption of trade-offs between environmental and economic performance. Mischaracterization of firms and production leads, in turn, both to overestimates of the cost of reducing GHGs and to an overly narrow focus on GHG policy choices that "have to hurt." Conventional models cannot analyze policies such as promoting voluntary initiatives by firms to reduce their emissions, fostering changes in corporate culture, or developing standardized methods for benchmarking a firm's environmental management.

Based on the insights of the new institutional economists, business historians, and organizational theorists, it is possible to improve the way firms are modeled in climate policy analysis. This more realistic approach makes clear that economic and environmental performance can be enhanced simultaneously through technological and organizational innovation. The challenge for economists is to develop ways to integrate the modern theory of the firm into the forecasting and simulation analyses used to estimate the costs and benefits of GHG reduction policies. The challenge for policy-makers is to encourage firms to innovate in multiple dimensions to meet the dual objectives of climate protection and economic performance.

Endnotes

1. These include various decade- (or longer) scale economic and energy forecasting models, particularly those that seek to estimate the "cost to the economy" of alternative policies or targets for GHG emissions reductions. For example, Weyant and Hill (1999) reported the results of a set of Stanford Energy Modeling Forum runs of various "computable general equilibrium" (CGE) models estimating the impacts of the Kyoto Protocol (were it to be implemented). Computable general equilibrium models are representations of the entire economy as a set of equations, assuming maximizing behavior by the economic agents and specifying that all markets clear or are in equilibrium. The models are "computable" in the sense that the equations can be solved to yield predicted paths over time of the variables in the model. In scenarios allowing emissions trading among Annex I countries (the relatively wealthy industrialized countries), estimated costs to the United States of meeting the Kyoto target ranged from 0.2 percent to 0.9 percent of GDP in 2010, averaging 0.6 percent. This range does not include the estimate from the Oxford model, which is not a CGE model. If there is no trading among Annex I countries, the GDP loss is greater, ranging from 0.4 percent to 1.9 percent and averaging 1.2 percent.

In a similar vein, Laitner (1999, citing Council of Economic Advisers [1998]; Energy Information Administration, [1998]; Koomey et al., [1998]; Hanson and Laitner, [1998]; and Laitner, Hogan, and Hanson, [1999]) summarized the results of four analyses carried out by U.S. federal agencies on the potential impact on economic output and the path of technological change of implementing the Kyoto Protocol's targets. Two of these studies employed CGE models and two made use of "macroeconomic" models (models allowing for transitory unemployment). The GDP impacts as of 2010 ranged from a net gain of 0.6 percent to a net loss of 1.7 percent, and averaged a net loss of 0.2 percent.

Other examples of contemporary economic modeling of climate policies include Nordhaus (1994), Manne and Richels (1992), Goulder and Schneider (1999), Jorgenson and Wilcoxen (1993), Edmonds et al. (1992; see also Fisher-Vanden et al. [1993] and MacCracken et al. [1999]).

The estimates produced by models of this type vary considerably, and can even differ on whether the net impact of GHG reduction policies is positive or negative. It is known that the quantitative outcomes depend to a large degree on the particular assumptions made at the outset of the modeling exercise (Repetto and Austin [1997]).

2. In some models, the role of the production function in some sector(s) is played by linear programming routines that select technologies, or by estimated supply curves and/or substitution possibilities. In all these cases, some sort of underlying mathematical relationship between inputs, outputs, prices, and other variables in the model is assumed. To avoid repetition, these specifications will all be described as the "production function" approach.

3. For earlier references and a review, see DeCanio (1993).

4. Simon won the Nobel Prize in economics in 1978 for his work on bounded rationality.

5. A comprehensive survey of the bounded rationality literature is given by Conlisk (1996). See DeCanio (1999) for implications for climate policy analysis.

6. No attempt will be made to review or summarize here the vast amount of work that has been done in the other fields. See Carley (1999), Page and Ryall (1998), Burton and Obel (1995), and Carley and Prietula (1994) for the flavor of this literature.

7. An example of the kind of expedient resorted to in the conventional models is the choice of an exogenous rate of "autonomous energy efficiency improvement" (AEEI) based on historical extrapolation or analysts' judgment. Recent attempts to incorporate endogenous technological change into long-term growth models are described in Chapter II above, although these efforts have not been based on detailed analysis of what goes on inside firms. Section C of this chapter discusses one example of an attempt to model how technology diffusion occurs within firms.

8. The production possibility frontier is defined as the set of outputs such that an increase in any one must be accompanied by a decrease in another (or others). In other words, the frontier represents the best the firm can do, in terms of producing outputs, given a specified combination of inputs.

9. "Environmental quality" may be thought of as the inverse of emissions of pollutants. The production-possibilities frontier could just as easily have been drawn showing a trade-off between ordinary output and emissions, with lower emissions possible only with lower levels of ordinary output. Environmental quality is used on the vertical axis in keeping with the convention of showing the production-possibility frontier in terms of desirable goods.

10. Diagrams of this type have been presented in Bruce et al. (1996) and DeCanio (1997).

11. Recent detailed "bottom-up" engineering-economic studies have established that these opportunities can be found across all the major sectors of the economy. A review of such studies is given in Union of Concerned Scientists and Tellus Institute (1998). The most comprehensive recent bottom-up study is Interlaboratory Working Group (1997), with a follow-up due to be published late in 2000. See also the special issue of *Energy Policy* edited by Bernow et al. (1998). Additional literature is cited in DeCanio (1998).

12. It makes no difference here whether the "agents" making up the firm are individuals, teams, divisions, or other functional units within the organization.

13. These are common examples, but of course their profitability in particular situations depends on the specific circumstances.

14. The terminology "associative task" has come into use to describe this type of stylized activity for historical reasons that are described in DeCanio et al. (1999).

15. As noted above, the environmental impact of an organization is represented in the model by the organization's speed in adopting profitable energy-saving technologies.

16. It should be kept in mind that even in the conventional framework with a trade-off between (currently unpriced) environmental objectives and ordinary output, the introduction of environmental protection policies can be welfare improving due to the environmental benefits.

References

Alchian, A.A., and S. Woodward. 1988. "The Firm is Dead; Long Live the Firm: A Review of Oliver E. Williamson's The *Economic Institutions of Capitalism." Journal of Economic Literature* 26(1): 65-79.

Amano, A. 1997. "On Some Integrated Assessment Modeling Debates." Paper presented at the IPCC Asia-Pacific Workshop on Integrated Assessment Models, United Nations University, Tokyo (March 10-12).

Andersen, S.O., and D.B. Zoi. 1993. "ICOLP: An EPA Perspective." *Machine Design* 65(8): 61-62.

Berle, A.A., and G.C. Means. 1932. *The Modern Corporation and Private Property*. New York: The MacMillan Company.

Bernow, S., M. Duckworth, and J. DeCicco. 1998. "Special Issue: Climate strategy for the United States: "bottom-up" analyses of CO_2 reductions, costs and benefits." *Energy Policy* 26(5).

Bovenberg, A.L., and S.A. Smulders. 1996. "Transitional Impacts of Environmental Policy in an Endogenous Growth Model." *International Economic Review* 37: 861-894.

Brock, W. 1977. "A Polluted Golden Age." In *Economics of Natural and Environmental Resources*. V. Smith, ed. New York: Gordon and Breach.

Bruce, J.P., H. Lee, and E.F. Haites, eds. 1996. *Climate Change: Economic and Social Dimensions of Climate Change.* Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Burton, R.M., and B. Obel. 1995. *Strategic Organizational Diagnosis and Design: Developing Theory for Application*. Boston, Kluwer Academic Publishers.

Carley, K.M. 1999. "Opening up the Black Box: Organizational Design as Dynamic Networks." Paper presented at the Pew Center on Global Climate Change Workshop on The Economics and Integrated Assessment of Climate (July).

Carley, K.M., and M.J. Prietula, eds. 1994. *Computational Organization Theory*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Coase, R. 1937. "On the nature of the firm." *Economica*, n.s. 4(16): 386-405.

Conlisk, J. 1996. "Why Bounded Rationality?" *Journal of Economic Literature* 34(2): 669-700.

Council of Economic Advisers. 1998. *The Kyoto Protocol and the President's Policies to Address Climate Change: Administration Economic Analysis*. Washington, DC (July).

DeCanio, S.J. 1993. "Barriers within firms to energy-efficient investments." *Energy Policy* 21(9): 906-914.

__________. 1997. "The False Trade-off between Environmental Protection and Economic Growth." *Contemporary Economic Policy* 15(4): 10-27.

__________. 1998. "The efficiency paradox: bureaucratic and organizational barriers to profitable energy-saving investments." *Energy Policy* 26(5): 441-454.

__________. 1999. "Estimating the Non-Environmental Consequences of Greenhouse Gas Reductions Is Harder than You Think." *Contemporary Economic Policy* 17(3): 279-295.

DeCanio, S.J., C. Dibble, and K. Amir-Atefi. 1999. "Structure and Performance in Multitask Organizations." Paper presented at the Pew Center on Global Climate Change Workshop on The Economics and Integrated Assessment of Climate Change, Washington DC (July).

Economic Options Committee. 1994. 1994 *Report of the Economic Options Committee*. Nairobi: United Nations Environment Programme.

Edmonds, J.A., H.M. Pitcher, D. Barns, R. Baron, and M.A. Wise. 1992. "Modeling Future Greenhouse Gas Emissions: The Second Generation Model Description." Draft Report, presented to the United Nations University Conference on Global Change and Modeling, Tokyo (October 1991).

Energy Information Administration. 1998. *Impacts of the Kyoto Protocol on U.S. Energy Markets and Economic Activity,* SR/OIAF/98-03. Washington, DC (September).

Fisher-Vanden, K., J.A. Edmonds, H. Pitcher, D. Barns, R. Baron, S. Kim, C. MacCracken, E.L. Malone, R.D. Sands, and M. Wise. 1993. "The Second Generation Model of Energy Use, the Economy, and Greenhouse Gas Emissions." Presentation to the Sixth Annual Federal Forecasters Conference, Crystal City (September).

Goulder, L.H., and S.H. Schneider. 1999. "Induced Technological Change and the Attractiveness of CO_2 Abatement Policies." *Resource and Energy Economics* 21(3-4): 211-253.

Hanson, D., and J.A. "Skip" Laitner. 1998. "The Economic Effects of Policies That Increase Investments in Cost Effective Energy-Efficient Technologies." Paper presented at the Symposium on Energy Policy after the Kyoto Climate Protocol, Illinois Economic Association (October 24; revised December 29, 1998).

Hawken, P., A. Lovins, and L.H. Lovins. 1999. *Natural Capitalism*. Boston: Little, Brown and Co.

Howarth, R.B. 1998. "An Overlapping Generations Model of Climate-Economy Interactions." *Scandinavian Journal of Economics* 100(3): 575-591.

Interlaboratory Working Group. 1997. *Scenarios of U.S. Carbon Reductions: Potential Impacts of Energy Technologies by 2010 and Beyond.* Lawrence Berkeley National Laboratory, Berkeley CA, and Oak Ridge National Laboratory, Oak Ridge, TN, LBNL-40533 and ORNL-444, September, http://www.ornl.gov/ORNL/Energy_Eff/CON444.

Jorgenson, D.W., and P.J. Wilcoxen. 1993. "Reducing U.S. Carbon Emissions: An Econometric General Equilibrium Assessment." *Resource and Energy Economics* 15: 7-25.

Koomey, J.G., R.C. Cooper, J.A. Laitner, R.J. Markel, and C. Marnay. 1998. *Technology and Greenhouse Gas Emissions: An Integrated Scenario Analysis Using the LBNL-NEMS Model*. LBNL-42054 and EPA 430-R-98-021, Lawrence Berkeley National Laboratory and U.S. Environmental Protection Agency (September).

Laitner, J.A. "Skip." 1999. "The Economic Effects of Climate Policies to Increase Investments in Cost-Effective, Energy-Efficient Technologies." Paper presented at 74th Annual WEA International Conference, San Diego, CA (July 9).

Laitner, J.A. "Skip," K. Hogan, and D. Hanson. 1999. "Technology and Greenhouse Gas Emissions: An Integrated Analysis of Policies that Increase Investments in Cost Effective Energy-Efficient Technologies." Paper presented at the Electric Utilities Environment Conference, Tucson, Arizona (January 11). EPA Office of Atmospheric Programs, Washington, DC.

MacCracken, C.N., J.A. Edmonds, S.H. Kim, and R.D. Sands. 1999. "The Economics of the Kyoto Protocol." *Energy Journal*, Special Issue, "The Costs of the Kyoto Protocol — a Multi-Model Evaluation."

Manne, A.S., and R.G. Richels. 1992. *Buying Greenhouse Insurance: The Economic Costs of Carbon Dioxide Emission Limits.* Cambridge, MA: The M.I.T. Press.

Nelson, K. 1994. “Finding and Implementing Projects that Reduce Waste.” In *Industrial Ecology and Global Change.* R. Socolow, C. Andrews, F. Berkhout, and V. Thomas, eds. Cambridge, England: Cambridge University Press.

Nordhaus, W.D. 1994. *Managing the Global Commons: The Economics of Climate Change*. Cambridge, MA: The M.I.T. Press.

Page, S.E., and M. Ryall. 1998. “Does Strategy Need Computer Experimentation?” *Advances in Strategic Management: Disciplinary Roots of Strategic Management Research,* Vol. 15 (Series ed. Joel A. C. Baum). Stamford, CT: JAI Press, Inc.

Palmer, K., W.E. Oates, and P. Portney. 1995. “Tightening Environmental Standards: The Benefit-Cost or the No-Cost Paradigm?” *Journal of Economic Perspectives* 9(4): 119-132.

Porter, M.E. 1991. “America’s Green Strategy: Environmental Standards and Competitiveness.” *Scientific American* 264(4): 168.

Porter, M.E., and C. van der Linde. 1995a. “Toward a New Conception of the Environment-Competitiveness Relationship.” *Journal of Economic Perspectives* 9(4): 97-118.

__________. 1995b. “Green and Competitive: Breaking the Stalemate.” *Harvard Business Review* 73(5): 120-134.

Raff, D.M.G., and P. Temin. 1991. “Business History and Recent Economic Theory: Imperfect Information, Incentives, and the Internal Organization of Firms.” In *Inside the Business Enterprise: Historical Perspectives on the Use of Information*. P. Temin, ed. Chicago: The University of Chicago Press.

Repetto, R., and D. Austin. 1997. *The Costs of Climate Protection: A Guide for the Perplexed.* Washington, DC: World Resources Institute.

Romm, J.J. 1994. *Lean and Clean Management: How to Boost Profits and Productivity by Reducing Pollution.* New York: Kodansha America, Inc.

__________. 1999. *Cool Companies: How the Best Businesses Boost Profits and Productivity by Cutting Greenhouse Gas Emissions.* Washington DC: Island Press.

Sanstad, A. 1999. “Endogenous Technological Change and the Crowding Out Problem in Climate Policy.” Paper presented at the Conference on Economics and Integrated Assessment, Pew Center on Global Climate Change, Washington DC (July).

Tol, R.S.J. 1994. “The Damage Costs of Climate Change: A Note on Tangibles and Intangibles, Applied to DICE.” *Energy Policy* 22(5): 436-438.

Union of Concerned Scientists and Tellus Institute. 1998. A Small Price to Pay: *US Action to Curb Global Warming Is Feasible and Affordable*. Cambridge, MA: UCS Publications.

von Weitzsäcker, E., A.B. Lovins, and L.H. Lovins. 1997. *Factor Four: Doubling Wealth — Halving Resource Use*. London: Earthscan Publications Ltd.

Wexler, P. 1996. “Saying Yes to ‘No Clean.’” In *Ozone Protection in the United States: Elements of Success*. Elizabeth Cook, ed. Washington, DC: World Resources Institute.

Weyant, J.P., and J.N. Hill. 1999. “The Kyoto Protocol: A Cost-Effective Strategy for Meeting Environmental Objectives?” *The Energy Journal*, Special Issue.

Williamson, O.E. 1985. *The Economic Institutions of Capitalism: Firms, Markets, Relational Contracting*. New York: The Free Press.

__________. 1998. “Transaction Cost Economics: How it Works; Where it is Headed.” *De Economist* 146(1): 23-58.

IV. Climate Change and Intergenerational Fairness

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A. Introduction

Questions of intergenerational fairness are an essential component of climate change policy debates. It is widely recognized that the costs of GHG emissions abatement will fall in substantial measure on the producers and consumers of the early- to mid-twenty-first century. The benefits of sustained climatic stability, in contrast, will accrue to individuals and societies living decades and perhaps centuries into the future. The design of optimal response strategies therefore depends strongly on the criteria used to balance the interests of present and future generations.

Economic models of climate-economy interactions typically approach this problem using the concepts and methods of cost-benefit analysis (IPCC [1996a]). The analyst invokes assumptions regarding the monetary value of the benefits generated by environmental quality and the economic costs of climate change mitigation measures. Costs and benefits that occur in the future are then "discounted" relative to the present. Discounting accounts for the perceived time preference of decision-makers, who prefer to incur benefits sooner and costs later. By maximizing the discounted net benefits of emissions abatement, the analyst identifies an "optimal" (or economically efficient) policy portfolio. Under standard assumptions, this approach suggests that comparatively low rates of GHG emissions control are economically warranted (Nordhaus [1994]).

In recent years, skepticism has mounted among both analysts and policy-makers regarding the use of the cost-benefit framework to evaluate climate change policy options. This skepticism is attributable to issues of uncertainty as well as ethics. In terms of uncertainty, accurate cost-benefit analysis requires quite substantial amounts of data and information. Yet deep uncertainty surrounds both the physical impacts of climate change and the value of environmental services to future society. Woodward and Bishop (1997) argue that questions of risk are poorly addressed in the current set of climate-economy models. According to these authors, conventional cost-benefit analysis understates the value of precautionary action to reduce the threat of poorly understood, but potentially catastrophic, climatic impacts.

In terms of ethics, critics allege that the discounting procedures of conventional cost-benefit analysis involve the unfair treatment of future generations. Nordhaus, for example, follows the standard practice of discounting future monetary benefits at an annual rate of roughly 6 percent — an assumption that implies that one dollar of benefits obtained one century in the future is worth less than one cent of benefits to contemporary society. Since conventional cost-benefit analysis attaches essentially no weight to the interests of future generations, cost-benefit reasoning suggests that it might be “optimal” to impose great burdens on posterity to achieve relatively modest short-term benefits. Critics allege that a decision of this sort would be difficult to reconcile with principles of fairness.

The rationale for discounting is well known in economics. In markets for savings and investment, individuals voluntarily agree to make interest payments to obtain loans that finance short-term expenditures. A person who takes out a 30-year home loan at a 6 percent annual interest rate, for example, indicates a willingness to pay over ten dollars three decades hence to obtain just one dollar in the present. In a similar vein, creditors demand a positive return on investment in exchange for their decision to defer present consumption until some future date. In a world where (all else equal) people desire their benefits sooner and their costs later, market interest rates provide a measure of the rate at which people discount the future in their own personal decisions. The cost-benefit criterion applies this private preference to social decisions concerning environmental policy.

The philosophical issues surrounding discounting procedures have spawned vociferous debate in both policy circles and the academic community. Nordhaus, for example, argues that climate change policies should be evaluated by the same criteria that private individuals use in evaluating investment options. According to this logic, the discount rate employed in policy analysis should be equated with the market rate of return. Other analysts argue that notions of individual time preference that lie behind market choices are irrelevant to social decisions concerning trade-offs between the welfare of present and future generations. Parfit (1983), for example, argues, “the moral importance of future events does not decline at *n* percent per year. A mere difference in timing is in itself morally neutral.” Based on this reasoning, Parfit rejects the use of discounting.

The present analysis defers judgment on the merits of these moral arguments, focusing instead on the implications of alternative climate change response strategies for the welfare of present and future generations. The analysis employs a model of climate-economy interactions that explicitly accounts for the interplay between producers and consumers in a market economy, and for the role of public policies in governing the global environment.

The study examines the implications of two major ethical frameworks in addition to conventional cost-benefit analysis. The first, which is based on the views of environmental conservationists, holds that present decisions should strive to achieve sustained climatic stability for the benefit of future generations (Brown [1998]). In this perspective, unconstrained GHG emissions impose uncompensated harms — including the potential for irreversible, catastrophic outcomes — that cannot be reconciled with the fair treatment of posterity. This position is closely tied to the stated objective of the Framework Convention on Climate Change, which calls for the "stabilization of GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."

The second approach is based on the libertarian view that government intrusion on economic freedom should be limited to the fullest extent possible (Gray and Rivkin [1991]). According to this perspective, future generations are likely to enjoy living standards far better than those available in today's society. In effect, costly efforts to control GHG emissions so that future generations might benefit from improved environmental quality amount to a transfer of income from relatively poor individuals in the present to relatively rich members of future generations.

To be sure, the conservationist and libertarian perspectives differ substantially in their underlying factual assumptions. Environmentalists tend to believe that climate change will impose quite substantial and irreversible environmental costs, and that near-term GHG emissions abatement would be relatively inexpensive. Libertarians, in contrast, see environmental regulations as inherently costly, while often questioning the benefits of present action to avoid future climate change. Libertarians tend to be more optimistic that the impacts of climate change will be relatively minor, or that future generations will be better able to avoid, or adapt to, these impacts. It should not be forgotten, however, that these views reflect significant disagreements concerning the relative importance of pure market liberty and the need to protect the natural environment for the sake of future generations. This paper will show that the climate change policies that emerge from these frameworks have interesting consequences for the distribution of welfare between present and future generations.

B. Analytical Approach

The issue of intergenerational fairness is often sidestepped by economic analyses of climate-economy interactions for two major reasons. First, analysts tend to emphasize the short-term costs of GHG emissions abatement and the potential impacts of climate change over the next ten to one hundred years. While this time scale is of course much longer than those employed in routine policy analysis, the fact remains that the full impacts of climate change are likely to intensify over the course of several centuries. Understanding the impacts of emissions abatement policies on the welfare of posterity therefore requires analysts to peer into the distant future.

Second, although climate change will impose differential impacts on the welfare of present and future generations, the standard models employed in the economics of climate change (see Nordhaus [1994]) fail to account explicitly for the standpoint of future generations. Such models assume that conventional cost-benefit analysis offers a unique measure of "social welfare" that must, of necessity, be used to identify "optimal" policies. In technical terms, this approach is implemented by assuming that the economy behaves as if decisions regarding economy-environment trade-offs were made by a single generation of human beings whose lives stretched from the present into the long-term distant future. This single generation employs conventional discounting, which gives very little weight to the very long term. While this approach may be sensible for analyzing problems with relatively short time horizons, it obscures the ways in which climate change policies will affect the distinct interests and welfare of present and future generations.

To address these problems, the present study assesses the costs and benefits of climate change over a quite long time horizon, emphasizing the impacts of alternative policy scenarios over the next four hundred years. In addition, the analysis makes use of a so-called "overlapping generations" model (see Howarth and Norgaard [1995]) in which the long-term behavior of the world economy is simulated in a way that accounts for the separate decisions that members of present and future generations will make over the course of their life spans. In place of a single measure of social welfare, the model explicitly accounts for the impacts of climate change policies on the well-being of both present and future generations. Taking this approach sheds significant light on the questions of intergenerational fairness that are so central to climate change policy debates.

The details of the model are described in the Appendix. Before turning to the results, however, it is useful to provide a brief synopsis of the model's main characteristics so that the findings of the analysis may be viewed in proper context. At a general level, the model represents the interplay between the world economy and the global environment under the assumptions developed by Nordhaus (1994) concerning population growth, technological change, and climate dynamics. But although Nordhaus stresses the cost-benefit criterion in a model that does not distinguish between the welfare of present and future generations, the present model adapts his approach to account for the two issues identified above. The work of Nordhaus was chosen for this purpose because it is arguably the best known and most influential in the existing literature.

In the analysis presented here, routine economic decisions regarding production, consumption, and investment are made by private individuals in the context of a market economy. Production is carried out by competitive firms that use inputs of capital and labor while generating GHG emissions as a by-product. Following Nordhaus, the model assumes that emissions abatement is economically costly, with a 50 percent emissions control rate reducing economic output by 0.9 percent. Unchecked emissions of GHGs, however, give rise to environmental impacts such as sea-level rise, reduced agricultural productivity, biodiversity loss, storm intensification, and the spread of tropical disease. The value of these impacts is measured in monetary terms under the assumption that a 3.0 ºC increase in mean global temperature imposes costs equivalent to 1.33 percent of economic output (Nordhaus [1994]).

C. Policy Scenarios

The analysis here considers the implications of three policy regimes that are based on alternative assumptions concerning how climate change policy decisions should respond to the perceived interests of present and future generations. As was noted above, the model assumes that routine economic decisions are made by producers and consumers in the context of free markets. However, since GHG emissions impose environmental costs that are not reflected in market prices, there is a potential role for public policy in climate change.

The first scenario, the *laissez-faire* baseline, is based on the libertarian perspective that decisions regarding pollution control should be left in the hands of producers and consumers. Although the government plays a role in defending private property claims and protecting citizens against fraud and coercion, GHG emissions remain unregulated in this model simulation.

The second scenario, the climate stabilization case, is based on the conservationist view that future generations should enjoy the benefits of an undamaged natural environment. In this scenario, CO_2 emissions are limited to the rate at which GHGs are removed from the atmosphere via natural processes so that mean global temperature remains constant at its current (year 2000) level. The government implements emissions targets by imposing a carbon tax on private sector firms, and returning the tax revenues to citizens.

Since both the *laissez-faire* baseline and the *climate stabilization* scenario base public policy on the strict protection of either market liberty or environmental quality without balancing the costs and benefits of GHG emissions, both are subject to the criticism that they fail to attain economic efficiency. A policy regime is said to be economically efficient if it is impossible to enhance the welfare of one or more members of society without making another worse off. According to economic theory, a policy is efficient if it maximizes the discounted value of net monetary benefits over time (Howarth and Norgaard [1995]).

Based on this standard theoretical argument, the third scenario bases climate change policy decisions on conventional cost-benefit analysis, taxing GHG emissions to account for the incremental costs they impose on future society, and returning the resulting tax revenues to consumers. In this scenario, the discount rate is set equal to the market rate of interest, which reflects the preferences that individuals express regarding trade-offs between costs and benefits that are realized at different points in time.

Basing social choices concerning intergenerational trade-offs on the discount rates that people use in their private decisions is a controversial practice. Broome (1992), for example, advocates an approach in which costs and benefits are measured in terms of human well-being rather than monetary units, with equal weight attached to the welfare of present and future generations. The achievement of economic efficiency through monetary cost-benefit analysis, however, requires the use of discount rates that reflect individual time preference. (See Howarth [1998] for a further discussion of these issues.)

1. Scenario Results

As expected, the distinction between the *laissez-faire* and climate stabilization scenarios makes a pronounced difference in terms of the evolving links between economic activity and environmental quality (see Table 1). In each scenario, the world economy develops from its initial state towards a long-term equilibrium in which all variables are (approximately) constant from the years 2420 onward. For purposes of discussion, it is useful to interpret the year 2000 as the "short-term" and the year 2420 as the "long-term future."

Table 1

Simulation Results — Base Model Runs

Year	2000	2105	2420
Consumption (1989 $/person/year)			
Laissez-faire	4,058	10,467	14,664
Climate stabilization	3,791	10,027	15,271
Cost-benefit analysis	4,058	10,542	15,043
Carbon Tax (1989 $/metric ton)			
Laissez-faire	0	0	0
Climate stabilization	560	855	1,081
Cost-benefit analysis	16	56	76
Carbon Dioxide Emissions (billion metric tons-carbon/year)			
Laissez-faire	10.2	25.5	30.9
Climate stabilization	0.1	1.0	1.1
Cost-benefit analysis	8.6	19.6	23.9
Temperature Increase (ºC)			
Laissez-faire	1.7	5.1	8.0
Climate stabilization	1.7	1.7	1.7
Cost-benefit analysis	1.7	4.6	7.1

In the absence of policy interventions, CO_2 emissions grow from 10.2 to 30.9 billion metric tons per year between the years 2000 and 2420, while mean global temperature rises by 8.0 ºC relative to the pre-industrial norm. A warming of this magnitude rivals the temperature changes associated with the passage from ice ages to interglacial periods, and would likely give rise to quite substantial ecological impacts. The climate stabilization scenario, in contrast, requires the limitation of CO_2 emissions to no more than 1.1 billion metric tons per year. Thus, quite stringent limitations on carbon emissions must be imposed to achieve climate stability. The carbon tax necessary to achieve these limitations is $560 per ton in the year 2000, increasing to $1,081 per ton by the year 2420. (Monetary units are measured in constant-value 1989 dollars throughout the analysis.) The precise rate of carbon control varies somewhat over time because of changes in the atmospheric stocks of non-carbon GHGs such as methane and nitrous oxide that the model assumes are independent of policy decisions. While one might question the finding that a $560 per ton carbon tax could generate emissions reductions as large as those described in this table, this result follows directly from Nordhaus' assumptions regarding emissions abatement costs. See Howarth and Monahan (1996) for a review and discussion.

The *laissez-faire* and climate stabilization scenarios also differ markedly with respect to the distribution of economic welfare, measured in terms of per capita consumption, between present and future generations. The use of consumption as a welfare measure deserves special comment. Conventional wisdom suggests that there may be a trade-off between the production of market goods and the achievement of environmental quality. The question therefore arises as to how per capita consumption accounts for the value of environmental services. Following the assumptions of Nordhaus, the model assumes that climate change damages occur through negative impacts on production activities — reduced agricultural output, the flooding of coastal lands, increased health care costs, etc. Since production contributes to welfare through material consumption, "consumption" in this model accounts for the direct and indirect economic benefits that people derive from climate stability, as well as for the costs of GHG emissions abatement. However, it excludes benefits that cannot be estimated in dollar terms.

Under the *laissez-faire* scenario, the uncontrolled increase in mean global temperature imposes long run (year 2420) costs of $16 trillion per year, or 9 percent of economic output. The climate stabilization scenario, in contrast, imposes short-term (year 2000) costs of $1.7 trillion per year, or 7 percent of output. As one would expect, the *laissez-faire* scenario, in which per capita consumption rises from $4,058 to $14,664 per year between 2000 and 2420, tends to favor the interests of present producers and consumers. Under the climate stabilization scenario, in contrast, short-run consumption is reduced by 7 percent relative to the *laissez-faire* baseline, while long-term consumption is increased by 4 percent.

This result, while contingent on the particular assumptions of the model, points to an interesting and important qualitative conclusion. Libertarians sometimes argue that stringent efforts to conserve environmental quality will "lock up" the resources required to support a healthy economy, thus compromising the welfare of both present and future generations. Yet the present analysis suggests that climate stabilization might in fact substantially advance the interests of future generations in comparison with the *laissez-faire* baseline. In this context, the global environment is a valuable asset that generates flows of benefits to producers and consumers. Stabilizing climatic conditions for the benefit of future generations, enforced through strict limits on GHG emissions, augments the total wealth and life opportunities of future society. In the long run, a healthy environment and material prosperity go hand-in-hand in the climate stabilization scenario.

As was discussed in the preceding section, neither the *laissez-faire* nor the climate stabilization scenario explicitly balances the costs and benefits of GHG emissions abatement. Accordingly, neither of these cases conforms to the goal of economic efficiency that supports the use of cost-benefit analysis. One might suppose that making climate change policy choices through appeals to cost-benefit analysis would confer significant benefits on both present and future generations.

The results of this analysis, however, suggest that this presumption is incorrect for the model here. In line with the earlier results of Nordhaus (1994), setting climate change policies according to cost-benefit criteria leads to relatively modest rates of GHG emissions abatement. In this scenario, CO_2 emissions rise from 8.6 to 23.9 billion metric tons between the years 2000 and 2420, with a long-term temperature increase of 7.1 ºC. The temperature changes are close to those that arise under the *laissez-faire* scenario, but the effective emissions reductions are 16 to 23 percent. Under the assumptions of this scenario, the use of discounting procedures implies that little weight is attached to impacts that occur in the distant future. Hence it is better to suffer the costs of future climate change than to bear the present costs of aggressive emissions control.

Quite notably, the cost-benefit scenario has essentially no impacts on short-term consumption or economic welfare in comparison with the *laissez-faire* baseline, but it generates a 3 percent gain in long run consumption. In comparison with the climate stabilization case, however, the cost-benefit scenario involves a 7 percent increase in short-term consumption but a 2 percent loss over the long-term future. Put somewhat differently, moving from climate stabilization to cost-benefit analysis imposes uncompensated costs of some $2.4 trillion per year on distant future generations. Of course, moving from *laissez-faire* to cost-benefit analysis yields gains of a similar magnitude. A conservationist might object that moving away from climate stabilization is morally unfair, just as a libertarian might object to imposing short-term economic costs for the benefit of the further future.

By looking at per capita consumption in particular years, one can see clearly the intergenerational trade-offs that are often obscured by discounting. Under the assumptions of the model, those living in the year 2420 would be worse off under *laissez-faire*, better off under cost-benefit analysis, and still better off under climate stabilization. Present producers and consumers, in contrast, would be better off under the *laissez-faire* and cost-benefit scenarios, and worse off under climate stabilization. Although the percentage differences in the material standard of living are smaller in 2420 than they are in 2000, they accumulate over a great many more years.

2. *"High Damage" Scenarios*

Following Nordhaus (1994), the base version of the model assumes that the costs of climate change will be relatively modest, so that a 3 ºC increase in mean global temperature will impose costs equivalent to 1.33 percent of economic output. Some analysts, however, question the validity of this assumption. Scientists warn that climate change may have unforeseen impacts — a disruption of ocean circulation patterns, an increase in the frequency and severity of extreme weather events, or substantial reductions in biodiversity — that might impose devastating damages on future generations (IPCC [1996b]; see also Chapter V of this report). To cover such contingencies, the analysis examines a set of "high damage" scenarios in which a 3 ºC temperature rise imposes costs equivalent to 13.3 percent of gross world output, so that impacts are ten times more severe than in the base case.

Under this assumption, the differences in welfare that occur under the *laissez-faire*, climate stabilization, and cost-benefit simulations are greatly accentuated (Table 2). In the *laissez-faire* case where CO_2 emissions remain uncontrolled, per capita consumption rises from $3,909 in the year 2000 to just $6,790 in 2420. A temperature increase of 5.8 ºC imposes costs equivalent to a 49 percent reduction in long-term economic output. The climate stabilization scenario, in contrast, gives rise to consumption levels that increase from $3,652 per person in the year 2000 to $14,533 in 2420. Relative to the *laissez-faire* baseline, a relatively small reduction in short-run consumption supports a 114 percent increase in long-term living standards. Under these circumstances, the choice between the policy objectives of market freedom and climate stabilization has crucial implications for the course of economic development.

Table 2

Simulation Results — High Damage Scenarios

Year	2000	2105	2420
Consumption (1989 $/person/year)			
Laissez-faire	3,909	6,883	6,790
Climate stabilization	3,652	9,545	14,533
Cost-benefit analysis	3,873	8,904	12,792
Carbon Tax (1989 $/metric ton)			
Laissez-faire	0	0	0
Climate stabilization	560	851	1,076
Cost-benefit analysis	153	525	803
Carbon Dioxide Emissions (billion metric tons-carbon/year)			
Laissez-faire	9.8	16.8	14.3
Climate stabilization	0.1	1.0	1.1
Cost-benefit analysis	4.7	5.2	4.3
Temperature Increase (ºC)			
Laissez-faire	1.7	4.7	5.8
Climate stabilization	1.7	1.7	1.7
Cost-benefit analysis	1.7	2.9	3.1

The "high damage" assumption gives rise to a cost-benefit optimum in which CO_2 emissions are limited to 4.7 billion metric tons in the year 2000 and 4.3 billion metric tons in the year 2420. The carbon tax necessary to achieve this carbon reduction is $153 per ton in the year 2000, rising to $803 per ton by the year 2420. Relative to the *laissez-faire* baseline, these figures represent emissions reductions of a full 52-70 percent. Under this scenario, the long-term increase in mean global temperature is limited to 3.1 ºC, which involves somewhat more than a doubling in GHG concentrations relative to the pre-industrial norm. In comparison with the *laissez-faire* baseline, the cost-benefit criterion imposes a short-term consumption loss of 1 percent that leads to an 88 percent increase in the long-term standard of living. In comparison with climate stabilization, however, cost-benefit analysis suggests policies that impose uncompensated *costs* of some $18 trillion per year on the long-term economy. Questions of intergenerational fairness must naturally be considered in evaluating the respective merits of these three scenarios.

D. Summary and Conclusions

Models in which the assumed policy objective is to maximize the discounted net benefits of GHG emissions abatement dominate the economic analysis of climate change. In this setting, costs and benefits are measured in monetary units, and the weight attached to the future impacts of climate change falls over time to account for the time preference that people express in routine decisions regarding savings and investment. This approach is exemplified by the well-known work of Nordhaus (1994), who constructs an "optimal growth" model in which societal decisions concerning consumption, investment, GHG emissions, and all other economic variables are made using a sophisticated version of cost-benefit analysis.

The analysis presented here departs from this existing literature in several respects. Rather than modeling policy decisions as though society consisted of just one generation of people who sought to balance the costs and benefits of climate change over their individual life spans, the present analysis employs an overlapping generations model that builds on the following facts: (1) people have finite life spans; and (2) the impacts of GHG emissions will affect the welfare of present and future generations in quite different ways. Put somewhat differently, the model supplants the notion that there is a single notion of "social welfare" that is captured by conventional cost-benefit criteria, instead looking at the trade-offs that exist between distinct measures of the well-being of people who live at different points in time. In this model, independent decisions are taken by producers, consumers, and policy-makers in the context of competitive markets. "Optimal growth" models, in contrast, are based on the notion of a hypothetical central planner who manages all aspects of the economy.

The main conclusions of the analysis may be summarized as follows. Under standard assumptions concerning the costs and benefits of climate change, conventional cost-benefit analysis supports relatively modest reductions in GHG emissions relative to a *laissez-faire* baseline in which emissions remain unregulated. These emissions reductions, which take into account the discounted value of future environmental quality, have almost no impact on short-term economic welfare but increase consumption by roughly 3 percent for the years 2420 and thereafter. These results are familiar from the existing literature and are not unique to this analysis.

But although the conventional wisdom asserts that the aggressive control of GHG emissions would impair economic efficiency to the detriment of both present and future society, the analysis presented here suggests a rather different conclusion. A climate stabilization scenario, in which mean global temperature is maintained at its current level into the long-term future, leads to a 7 percent reduction in short-term (year 2000) consumption in comparison with the *laissez-faire* baseline. Climate stabilization, however, supports long-term (year 2420) consumption levels that are $2.4-6.4 trillion per year *higher* than those that arise when pollution control is either left to the market or governed by conventional cost-benefit criteria. In an important sense, conservationists may be correct in their claims that climatic stability is an environmental asset that would confer substantial benefits on future generations, and that GHG emissions would impose uncompensated costs on the long-term economy.

Why do the findings of this analysis diverge so widely from the conventional wisdom? To answer this question, it is important to consider the key structural differences that exist between optimal growth and overlapping generations models. In optimal growth models, rates of capital investment are coordinated with environmental policies to maximize the central planner's conception of social welfare. In particular, steps to protect environmental quality for the benefit of future society are matched by reductions in the rate of capital investment. Hence if emissions abatement rates exceed their "optimal" (i.e. economically efficient) levels, the central planner chooses to spread the ensuing net costs over time so that both present and future society are made worse off. In overlapping generations models, in contrast, steps to protect environmental quality do not have similar effects on market decisions regarding capital investment, at least in the case where savings and investment are motivated by self-interest as opposed to an altruistic concern for future generations (see Howarth [2000]). Hence climate stabilization can provide benefits to future generations without causing offsetting reductions in capital accumulation. A similar issue arises in the so-called "Ricardian equivalence" literature in macroeconomics, which concerns the impacts of taxes and public expenditures on long-term economic performance. Although optimal growth models suggest that government budget deficits should have no impact on economic growth, Auerbach and Kotlikoff (1987) show that deficits can have major impacts in overlapping generations models.

The relative merits of the *laissez-faire*, climate stabilization, and cost-benefit scenarios must, of course, be judged through explicit appeals to ethical concepts. While some argue that today's producers and consumers should be free to pursue their interests in the absence of undue regulation, others argue that the benefits of an undiminished natural environment should be protected and sustained from generation to generation. How to combine these arguments with a concern for economic efficiency, in which policy strategies are evaluated in terms of their net monetary benefits, introduces philosophical issues that are beyond the scope of the present discussion.

Finally, the analysis considers a set of "high damage" scenarios in which a 3.0 ºC increase in mean global temperature would impose environmental costs equivalent to about 13 percent of economic output — a level that is ten times higher than the losses that occur in the base version of the model. Under this assumption, the cost-benefit criterion suggests emissions control rates that rise from 52 percent to 69 percent between the years 2000 and 2105, and the failure to reduce GHG emissions leads to dramatic reductions in long-term economic growth. Since this empirical assumption is within the bounds of respected expert opinion, this result suggests that it is not safe to assume that climate change will impose small and manageable costs on posterity. As Woodward and Bishop (1997) point out, the threat of climate change involves questions of risk and uncertainty that are not easily resolved using conventional economic methods.

References

Auerbach, A.J. and L.J. Kotlikoff. 1987. *Dynamic Fiscal Policy*. Cambridge University Press, New York.

Broome, J. 1992. *Counting the Cost of Global Warming*. White Horse Press, Cambridge.

Brown, P.G. 1998. "Toward an Economics of Stewardship: The Case of Climate." *Ecological Economics* 26: 11-21.

Gray, C.B. and D.B. Rivkin. 1991. "A No Regrets Environmental Policy." *Foreign Policy* 83: 47-64.

Howarth, R.B. 1998. "An Overlapping Generations Model of Climate-Economy Interactions." *Scandinavian Journal of Economics* 100: 575-591.

Howarth, R.B. 2000. "Climate Change and the Representative Agent." *Environmental and Resource Economics* 15: 135-148.

Howarth, R.B. and P.A. Monahan. 1996. "Economics, Ethics, and Climate Change: Framing the Debate." *Global and Planetary Change* 11: 187-199.

Howarth, R.B. and R.B. Norgaard. 1995. "Intergenerational Choices under Global Environmental Change." In *Handbook of Environmental Economics*. D.W. Bromley, ed. Basil Blackwell, Oxford.

Intergovernmental Panel on Climate Change (IPCC). 1996a. *Climate Change 1995: Economic and Social Dimensions of Climate Change*. Cambridge University Press, New York.

Intergovernmental Panel on Climate Change (IPCC). 1996b. *Climate Change 1995: The Science of Climate Change.* Cambridge University Press, New York.

Nordhaus, W.D. 1994. *Managing the Global Commons: The Economics of Climate Change*. MIT Press, Cambridge, Massachusetts.

Parfit, D. 1983. "Energy Policy and the Further Future: The Social Discount Rate." In *Energy and the Future*. D. MacLean and P.G. Brown, eds. Rowman and Littlefield, Totowa, New Jersey.

Woodward, R.T. and R.C. Bishop. 1997. "How to Decide When Experts Disagree: Uncertainty-Based Choice Rules in Environmental Policy." *Land Economics* 73: 492-507.

Appendix: Overlapping Generations Model Description

The analysis described above employs a simplified model of the links between climate change and the world economy that was developed by Howarth (1998). The assumptions of this model are based on the well-known work of Nordhaus (1994), who provides a concise representation of climate dynamics and the technical determinants of economic growth. Nordhaus focuses on an “optimal growth” model in which societal decisions concerning consumption, investment, and other economic variables are based on the principles of cost-benefit analysis. The present study, on the other hand, makes use of an alternative specification in which the behavior of the overall economy is determined by the individual decisions of producers and consumers.

The model considers a market economy in which goods and services are produced using inputs of capital and labor. Economic output is divided between consumption and investment, and production is carried out by competitive firms seeking to maximize their profits given the prevailing prices of inputs and outputs. In the model, and in reality, wages and salaries account for three quarters of the value of economic output while capital accounts for the remainder. The assumption in the model is that (given fixed inputs) technological change augments the level of output at an initial rate of 1.4 percent per year. In line with standard demographic projections, human population rises from its present level of about 6.0 billion persons to 10.5 billion in the long run future. Population growth is concentrated in the next one hundred years, during which four-fifths of the total increase occurs. The model assumes that the supply of labor is proportional to total population. Individuals earn wage income by providing labor services to employers in the production sector.

Decisions concerning savings and investment are made by private individuals. A typical person lives for seventy years, investing part of her income in youth to finance increased consumption in old age. Savings are invested in capital goods at the prevailing interest rate, which reflects the incremental contribution that increased wealth makes to future economic activity. The model's assumptions about consumer preferences are chosen to match expected rates of economic growth.

The model assumes that emissions of CO_2 increase in proportion to economic output. In the absence of emissions abatement policies, emissions in the year 2000 amount to some 0.37 kg-carbon per dollar of output. Due to technological innovation, the ratio of emissions per unit output falls at an initial rate of 0.55 percent per year. The model assumes that emissions abatement, although technologically feasible, is economically costly. A 50 percent reduction in CO_2 emissions requires a 0.93 percent reduction in economic output. Abatement costs rise to 6.86 percent of economic activity when emissions are fully controlled.

The model rests on a simple, but analytically tractable, representation of climate dynamics. Approximately two-thirds of CO_2 emissions go into the atmosphere, while the remaining third is absorbed by the biota and the surface waters of the oceans. Once in the atmosphere, a typical CO_2 molecule remains airborne for 120 years. Thus anthropogenic emissions of CO_2 are removed from the atmosphere to the deep ocean at an effective rate of 0.833 percent per year.

Climate change is driven by the accumulation of both CO_2 and other GHGs in the atmosphere. The model treats stocks and flows of non-CO_2 GHGs as beyond the control of policy decisions; as the model is specified, these gases (which include chlorofluorocarbons, nitrous oxide, and methane) elevate mean global temperature at a rate that rises from 0.47 ºC in the year 2000 to 1.0 ºC in the long run future. The impacts of these gases, however, are small in magnitude when compared with the influence of CO_2. The model assumes that mean global temperature increases with the level of total GHG concentrations, measured in terms of CO_2 equivalent. A doubling of GHG concentrations relative to the pre-industrial norm (i.e., the prevailing conditions of the late nineteenth century) causes a net temperature increase of 2.91 ºC.

A critical aspect of the model is its assumptions concerning the damages imposed by climate change. Following Nordhaus (1994), the model assumes that a 3.0 ºC temperature increase imposes environmental costs equivalent to a 1.33 percent reduction in economic output, while a 6.0 ºC temperature increase leads to a 5.32 percent output loss. The level of damages is proportional to economic activity.

V. A Simple Climate Model Used in Economic Studies of Global Change

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A. Taking Surprises into Account

Analysts need to do a better job of characterizing climate "surprises" — the low-probability but high-consequence scenarios — that are driving much of the international concern about climate change. Currently, most analyses rely on models or projections that assume "smooth behavior" — i.e., the climate responds slowly and predictably, gradually warming as atmospheric GHG concentrations increase. In reality, the global climate is a complex system that could behave quite erratically. The circumstances that could drive such behavior have to do with physical and biological characteristics of the climate system itself, as well as the rate of GHG buildup.

This paper describes a climate model that is both simple enough to use in economic studies, and complex enough to explore the causes and consequences of one major type of "climate surprise" — the weakening and even collapse of the "conveyor belt" circulation of the North Atlantic Ocean. This particular climate surprise is probably the best-understood and largest plausible effect of its kind. The model will enable researchers and policy-makers to see more clearly the range of possible futures that could result from current policy choices.

B. Coupling of Simple Climate and Economic Models

Climate policy analysis increasingly has relied on integrated assessment models (IAMs) which couple climate models to economic models to derive "optimal" carbon abatement measures. Because of its simplicity and relative transparency, the Nordhaus (1992) Dynamic Integrated Climate Economy (DICE) model is widely used. Such IAMs often make numerous simplifying assumptions in all sub-components. This has led to a number of critical studies pointing out that alternative — but comparably plausible — sets of structural assumptions can produce very different results. In particular, researchers have studied alternative assumptions about: (1) the mechanisms and rates at which nature removes carbon from the atmosphere; (2) discount rates (which express society's preference to obtain benefits sooner and incur costs later); and (3) technology improvement.

Such optimizing IAMs determine the optimal carbon control rate by balancing the economic costs of climate policy — usually a carbon tax imposed on a perfectly functioning market economy — against the economic costs of unabated CO_2 buildup. That buildup causes climate change — calculated by a simple climate sub-model — which, in turn, is assumed to create "climate damage." Nordhaus (1992) uses only one "damage function" (i.e., the assumed mathematical relationship between the amount of climate change and the loss of economic assets associated with that level of climate change) in his DICE model. DICE is a simple energy-economy model for the aggregate world economy coupled to the comparably simple "two-box" (ocean and atmosphere) global-scale climate model of Schneider and Thompson (1981).

Even though DICE is a model with smoothly varying components (i.e., no "surprises" built in), it is still quite sensitive to assumed climate damage relationships. Roughgarden and Schneider (1999) used a probability distribution for damages to show this sensitivity. The resulting probability distributions for "optimal" carbon taxes show about a 5 percent chance that such a tax should be negative — i.e., a subsidy to fossil fuel burning. They also indicate that there is about a 5 percent chance that the optimal tax should be about $200 per ton carbon emitted, which would sharply curtail burning coal, and constrict oil consumption significantly. The only difference between these radically different policies is the assumed climate damage associated with a given level of smoothly varying climate change. While the use of a probability distribution of damage functions clearly expands the range of optimal policies the model "recommends," to date none of the many studies using DICE with alternative formulations or parameters[1] has used a climate model that produces rapid non-linear events.

The Schneider and Thompson (1981) model is capable only of smooth behavior. Smooth behavior is what most conventional analyses like DICE assume — i.e., a proportionate increase in temperature for each increment in GHG buildup, rather than abrupt or threshold climatic responses to smoothly increasing GHG concentrations. However, as noted in Houghton et al. (1996), "non linear systems when rapidly forced are subject to unexpected behavior." A non-linear system is one in which a given increment of forcing produces disproportionate responses — such as a "flip-flop" in ocean currents, or a rapid disintegration of an ice sheet.

Therefore, the authors extended the original "C" (for "Climate") in DICE to a new model. This new model, while retaining many of the properties of the smoothly varying 1981 Schneider/Thompson climate model, now includes mathematical relationships that allow it to mimic the behavior of complex three-dimensional coupled atmospheric and oceanic sub-models. In particular, the new model includes a non-linear effect of the rate of increase of GHG concentrations, which most current models neglect. The rate of GHG buildup may be as important a driver of climate effects as the absolute level, especially in causing climate surprises that might not otherwise have been triggered if GHG buildups were slower. Such complex models produce abrupt, non-linear behavior, in particular the collapse of the so-called "conveyor belt" circulation of the North Atlantic Ocean, when rapid GHG buildups are assumed.

The new model is designed to reproduce the climate behaviors anticipated by researchers in the climate community. The purpose here is to produce a tool that: (1) is relatively simple; (2) is capable of both exhibiting non-smooth behavior and taking into account the rate of GHG buildup; and (3) can be coupled to economic models like DICE and still be computationally efficient enough to allow many repeated simulations on modest computers. This new tool is called a Simple Climate Demonstrator (SCD), and its properties and performance are explained below.

C. The Need for an Improved Climate Model Component

Large, three-dimensional numerical models of Earth's climate system have been the reference standards for global change research for several decades (Washington and Parkinson [1986]). In the past, most of these models have been essentially atmospheric models with grossly simplified or non-existent representations of oceans. The 1990s saw the replacement of these earlier climate models with "fully coupled" (i.e., atmospheric sub-models joined with oceanic sub-models) atmosphere-ocean models that simulate ocean currents as well as atmospheric winds to represent better the actual interactive climate system (Houghton et al. [1996]).

The addition of an interactive and circulating ocean sub-model led to some interesting model behaviors that did not occur in the older atmosphere-only simulations. The appearance of El-Niño-like variability (i.e., a large oscillation in temperatures and precipitation across the Pacific Basin associated with radical shifts in drought and flood regimes) is one example. Perhaps more importantly, the new coupled models exhibit what was once thought of primarily as a mathematical curiosity, namely the ability to have two very different stable climate states for identical forcings (Manabe and Stouffer [1988], and

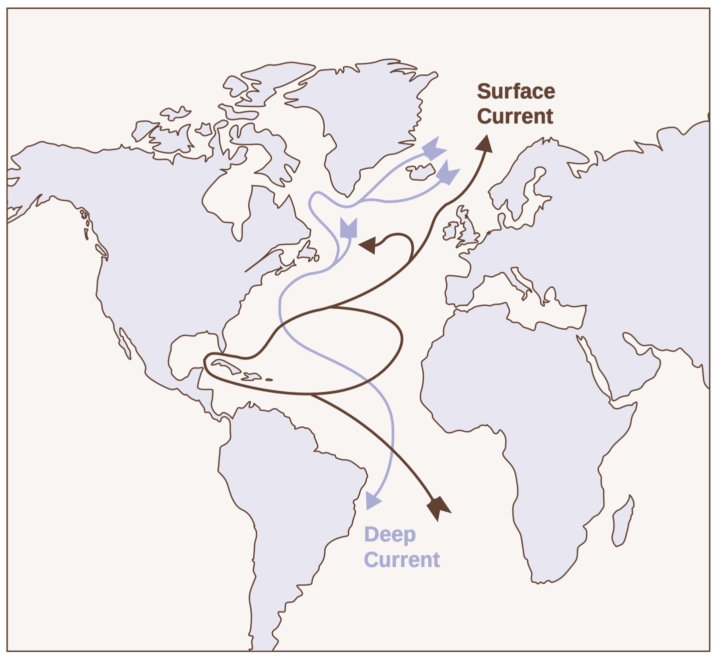
Rahmstorf [1995]). (Forcings are pressures put on the climate system from outside of the system. Changes in the heat output of the sun, or changes in the atmopheric concentrations of GHGs from human emissions, are examples of such "forcings." By analogy, the climate states can be likened to the two positions of a light switch (on or off), where each position is stable indefinitely unless modified by an external force (e.g., a finger pushing the switch with sufficient pressure)).

In the case of the Earth's climate over the past 10,000 years, the two stable states manifest themselves as two very different values for the strength of the overturning circulation in the Atlantic Ocean. The Gulf Stream that warms Europe is part of this circulation. This circulation, as depicted in Figure 1, is driven by the sinking of cold, dense water at high latitudes and forms part of the global ocean "conveyor belt" (Broecker [1991]). The circulation is called "thermohaline" because the density differences that drive it are determined by temperature and salinity differences. The thermohaline overturning circulation can be idealized as the sinking of dense plumes of water at high northern latitudes (blue lines in Figure 1), followed by transport southward in the deep ocean. Upwelling at lower latitudes and return flow northward in the upper ocean (brown lines in Figure 1) complete the circuit. The two modeled stable states for this flow are: (1) similar to present day, and (2) no conveyor belt flow at all. The "no flow" case is referred to as "overturning collapse" or the "thermohaline catastrophe."

Figure 1

A Map of the North Atlantic Ocean

Thermohaline Circulation



This "two-solution" behavior found in climate models would be a mere mathematical oddity if it were not for the profound influence of the Atlantic overturning circulation on climate, particularly the climate of the North Atlantic and western European region. Western Europe is up to 15 ºC warmer in winter than it would be if the heat transported northward by the thermohaline overturning circulation were to cease (e.g., Schneider et al. [1987]). Moreover, the potential for thermohaline circulation collapse is not just some model artifact. The paleoclimatic record clearly shows a dozen or more incidences of reduced or partially collapsed mode of thermohaline circulation. Why did the circulation change mode in the past? Scientists believe that, during glacial periods, the ice sheets partially collapsed, and discharged large amounts of freshwater into the North Atlantic in the form of massive iceberg releases (Broecker et al. [1985] and Seidov and Maslin [1999]). Because fresh water is less dense than salt water, this fresh water formed a layer at the surface of the Atlantic that inhibited sinking and encouraged sea ice formation. The sea ice, in turn, blocked the easy transfer of heat from the ocean to the air that blows over Europe. This caused much colder than normal conditions in Northern Europe. (See Figure 1 which shows the locations of the thermohaline circulation centers.)

Although the circulation went into weak circulation modes during cold climates in the past, this history is still highly relevant to a much warmer future. Any process that acts to lessen the density of the northern Atlantic Ocean can reduce or even collapse the overturning circulation. Freshwater has contributed to these changes during the most recent glacial period. Massive freshwater input from collapsing ice sheets cannot occur similarly today since the glacial age ice sheets are gone, but increasing temperature and precipitation from global warming may be another trigger for thermohaline collapse.

Warming directly reduces the density of surface oceanic waters, thereby causing a reduction in sinking potential. In addition, warming could result in atmospheric storms transporting more fresh water to the North Atlantic from enhanced evaporation in lower latitudes. Either process (direct warming, or injection of fresh water) would slow down both the sinking rate of cold water in the north, and the rate at which surface currents of waters from the south bring warm, salty water towards higher latitudes (e.g., the Gulf Stream in the case of the North Atlantic — see Figure 1). Because north-south temperature differences drive the transport of southern waters north, extra greenhouse heating in the north would reduce the northward flow of warm Gulf Stream waters. This reduction in warm inflow by itself would serve as a stabilizing negative feedback on the reduced circulation resulting from the initial warming. In other words, the reduction in the thermohaline circulation tends to be self-limiting. A circulation reduction allows the system to cool down, recreate dense surface waters, and thus maintain the sinking.

At the same time, however, reducing the strength of the Gulf Stream from either a warming or a freshening of northern surface waters would reduce the flow of salty subtropical water into the North Atlantic. This would reduce the salinity of the water, and thus further reduce cold water sinking, thereby serving as a destabilizing or positive feedback on the reduced overturning rate. The rate at which the system is pushed could determine whether the positive or negative feedbacks dominate, and control whether the thermohaline catastrophe occurs, or merely a weakening followed centuries later by a recovery.

Climate modelers now understand the importance of correctly simulating ocean circulation in their models. Current comprehensive models differ not only in their overall climate sensitivity, but also in how well they simulate the present-day thermohaline circulation and its response to global warming scenarios (Rahmstorf [1999]). Researchers developed simple climate models two decades ago (e.g., Schneider and Thompson [1981]) to aid in understanding the climate system, to explore transient (i.e., time-evolving) responses, and to facilitate coupling to other models, such as economic models. Further developments of such models have lagged behind in including the “on/off switch” non-linearities that are also called “surprise” scenarios (e.g., Houghton et al. [1996]).

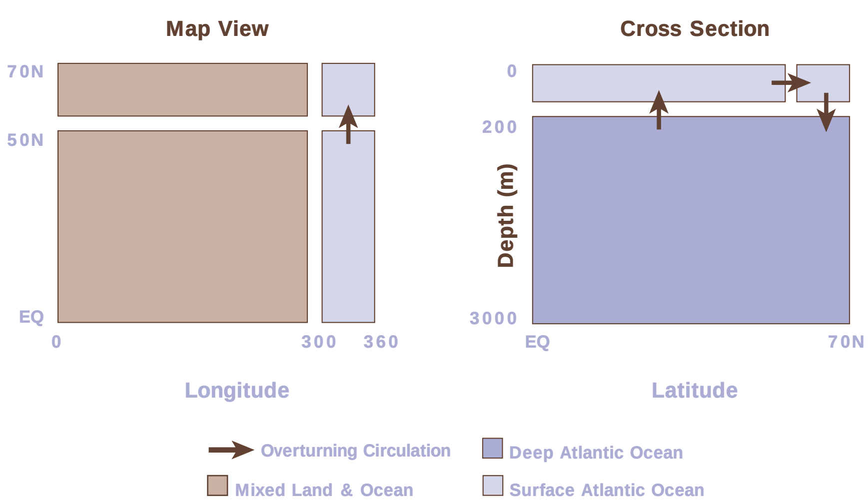
A goal for this study is to develop a “next-generation” simple climate model that would demonstrate behaviors similar to those found in much more complex models; hence the name “Simple Climate Demonstrator,” or SCD. Primary objectives are that the model be simple enough to understand thoroughly, and computationally efficient enough to be useful for coupling to similarly simplified economic models.

D. The Simple Climate Demonstrator Model

The SCD model represents the world as five geographic regions, or boxes, in the Northern Hemisphere (see Figure 2). Thus the authors assume *a priori* that the qualitative features of the climate system of interest can be reproduced with only the Northern Hemisphere. The fundamental properties of the boxes are their size, location and connectivity. As shown in Figure 2, there are four surface boxes and one deep ocean box.

Figure 2

The **Simple Climate Demonstrator** (SCD) Model



The two Atlantic sector surface boxes represent an idealized ocean 60º of longitude wide extending from the equator to 70º north (70N). This is a rough approximation of the geographic extent of the actual north Atlantic. The other two surface boxes represent the mixture of land and ocean that is "non-Atlantic" and are 300º of longitude wide. The latitude range of the northern boxes, 50N to 70N, is chosen to approximate the location of deep-water formation in the North Atlantic. The boxes of the SCD model are connected by flows of thermal energy and freshwater (or salinity). A modeled thermohaline overturning circulation connects the three ocean boxes. A further description of the SCD model is contained in the Appendix.

Numerous tests were done to characterize the response of the model to changes in climate forcing. As found in other models, SCD exhibits two stable states. One state has a substantial overturning circulation of about 20 Sverdrups (1 Sverdrup = 1Sv = one million cubic meters of seawater per second). The second state has no overturning. Lowering the density of the water in the northern upper ocean box can trigger a jump from the overturning to the no-overturning state. This can be accomplished by increasing either the temperature or the amount of freshwater injected, both of which are likely to occur with increasing CO_2. To move from the no-overturning collapsed state back to a "normal" circulation requires a large decrease in global temperature, or a large increase in salinity. The model produces a temporary, or transient, thermohaline circulation reduction or permanent collapse if the salinity of the northern upper ocean box is perturbed in a way that mimics a massive freshwater input from melting icebergs. Since the SCD model is designed to behave in this way, its ability to replicate this paleoclimatic history is comforting, but not definitive. More work will need to be done to see if the paleoclimatic record of the North Atlantic can be used to ensure that the SCD takes past climate behavior into account more precisely (see Rahmstorf and Ganopolski [1999], for further discussions).

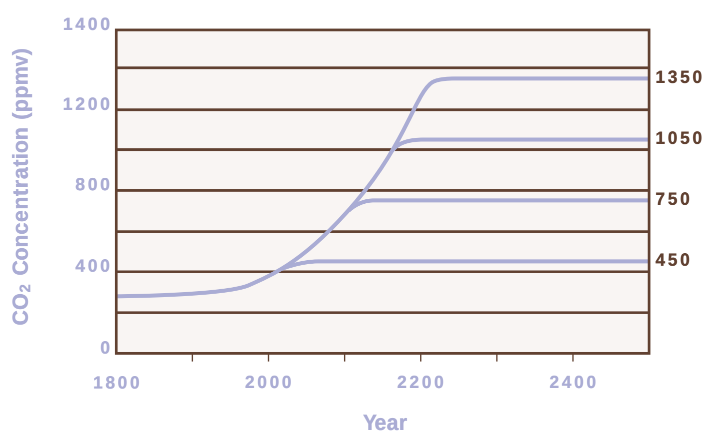
E. Global Warming Applications

1. Varying the CO_2 Stabilization Concentration

The SCD model was used to simulate global climate change from pre-industrial atmospheric concentrations of about 280 parts per million by volume (ppmv) CO_2 (current concentrations are about 370 ppmv) for the years 1800 to 2500 AD for four atmospheric CO_2 scenarios, as shown in Figure 3. In each case the CO_2 concentration follows the historical curve until 2000. After 2000, the concentration follows an approximation of the IPCC IS92a "Business as Usual" (BAU) curve, which effectively has a 0.61 percent per year exponential growth rate. The curves depart from the BAU exponential growth and stabilize at the arbitrary values of 450, 750, 1050, and 1350 ppmv. (The values of 450 and 750 ppmv have often been used to provide a plausible range of stabilization concentrations. However, larger atmospheric concentrations are expected for 2150 and beyond, unless

Figure 3

CO_2 **Stabilization Scenarios** Used in the SCD Model



Note: Four time-dependent atmospheric CO_2 concentration scenarios used in the SCD model. Each starts with the historical CO_2 increase to the present day, then moves into the future following the IPCC IS92a scenario. The effective exponential CO_2 increase rate after the year 2000 is 0.61% per year. Each scenario falls away from the exponential increase and stabilizes at the value shown.

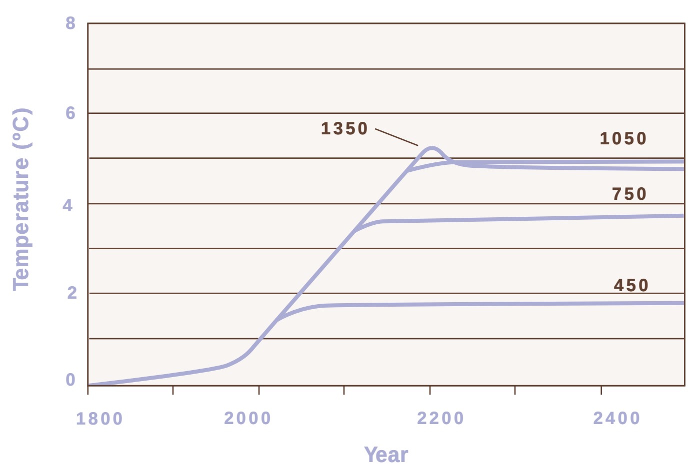
there is a significant shift away from fossil fuel-based energy systems, a major improvement in energy efficiency, or massive carbon sequestration[2] programs implemented over the next 50 to 100 years (e.g., Hoffert et al., [1998]). Even stabilizing CO_2 *emissions* sometime late in the twenty-first century at twice the present levels would lead to a century of more growth in CO_2 concentrations, which would stabilize in the twenty-second century at well above a doubling of present *concentrations*. Thus, the higher values of 1050 and 1350 ppmv are quite plausible scenarios as well, even though it is often assumed that humans would act to curb CO_2 emissions before such high concentration levels were reached. The model was run with a global climate sensitivity of 3.0 ºC (i.e., a 3.0 ºC global surface air temperature warming for an equilibrium[3] doubling of CO_2 concentrations). This sensitivity is in the middle of the IPCC range of 1.5 ºC to 4.5 ºC (Houghton et al., [1996]).

The global mean surface temperature change and the ocean circulation overturning strength are shown in Figures 4 and 5, respectively. The temperature response is straightforward except in the case of the highest CO_2 concentration. In this case, the temperature displays anomalous behavior at year 2200 and actually decreases below that of the next highest CO_2 concentration case (i.e., 1050 ppmv). The cause of the global temperature behavior can be found in the ocean circulation overturning strength (Figure 5). In the lower CO_2 concentration cases, increasing CO_2 causes the overturning to weaken temporarily. The overturning then slowly recovers to near 20 Sv as the time-dependent temperature and salinity perturbations fade after several thousand years of stabilized CO_2 concentrations (not shown).

In the highest CO_2 concentration case, the overturning circulation collapses permanently, as

Figure 4

Global Mean Temperature Response



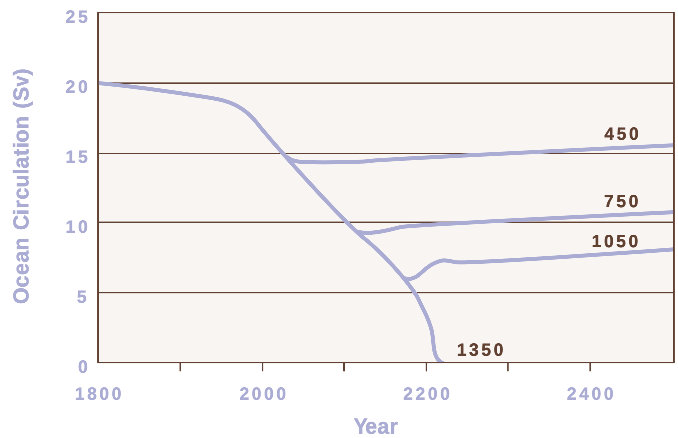
Note: Global average surface temperature change from the SCD model given the four CO_2 scenarios in Figure 3. In these cases, the model's climate sensitivity is 3.0 ºC (i.e., a global mean increase of 3 ºC for a climate in long-term equilibrium with doubled CO_2). Note that stabilizing at 1350 ppmv produces an anomalous cooling of the global temperature as a result of the collapse of the North Atlantic thermohaline overturning circulation.

opposed to merely slowing down. The overturning collapse causes a loss of heat transport to the north ocean surface box, which then cools substantially. This northern cooling increases snow cover and sea ice, thus actually reducing the global mean temperature compared to what it would be without the overturning collapse.

The model was tested to see if reducing the CO_2 concentrations back toward pre-industrial levels could force the collapsed circulation back to "normal." The model showed that the CO_2 concentration would have to be reduced to around 100 ppmv to accomplish this. This value is probably lower than has ever occurred on Earth, and is not likely to be photosynthetically acceptable for natural ecosystems and agriculture, even if it were physically possible to attain. An emergency reduction of the atmospheric CO_2 concentration is an unlikely remedy for reversing a thermohaline catastrophe once it occurs, given such non-linear, hysteresis behavior. (Hysteresis means that a system forced to change will not be restored to its previous state when that forcing is removed, but that an additional forcing in the opposite direction to the original forcing is needed to restore the system to its original state.)

Figure 5

North Atlantic Overturning **Circulation Response**



Note: Response of the North Atlantic overturning circulation strength for the four CO_2 scenarios shown in Figure 3. The present circulation strength is thought to be roughly 20 Sverdrups (Sv), where one Sv is defined as a million cubic meters per second. The strength of the overturning circulation decreases with increasing CO_2 until a point is reached where the overturning ceases entirely (the so-called thermohaline catastrophe).

The temperature response of the northern upper ocean box is very different depending on whether the overturning circulation collapses or not. This is as expected, and it agrees qualitatively with paleoclimatic observations and with several available simulations of this event (i.e., Schneider, Peteet, and North [1987] and Rahmstorf and Ganopolski, [1999]). After a thermohaline collapse, the north ocean box stabilizes at a temperature that is colder than the present day by about 8 ºC, even though the globe as a whole warms by 3.6 ºC. This would lead to the seemingly self-contradictory condition in which the world warms well beyond the range experienced over the past 10,000 years — the era during which human civilization evolved — while the North Atlantic, and quite possibly part of Northern Europe could cool. Such an event would clearly require revisiting the smoothly varying climate damage functions typically used in current generations of IAMs.

2. Varying the Climate Sensitivity

The actual sensitivity of the Earth's climate to CO_2 is unknown, but generally thought likely to be in the range of 1.5 to 4.5 ºC per CO_2 concentration doubling in equilibrium. However, many scientists assign subjective probabilities of some 10 percent to the possibility of climate sensitivity being outside (either greater or lower than) this range (e.g., Morgan and Keith [1995]). To test the dependence of the model's circulation response to its climate sensitivity, four simulations were performed with climate sensitivities of 1.5 ºC, 2.25 ºC, 3.0 ºC, and 4.5 ºC per CO_2 doubling. Each case uses the same CO_2 scenario, namely the 750-ppmv-stabilization case shown in Figure 3.

The ocean circulation temporarily slows by 25 percent to 50 percent in the cases having the three lowest sensitivities. The ocean circulation collapses at the highest climate sensitivity used here. In the case with circulation collapsing, neither the CO_2 stabilization value (750 ppmv) nor the high climate sensitivity (4.5 ºC) is implausible, although the climate sensitivity is near its generally accepted upper limit. In future simulations it would be more appropriate to use subjective probability distributions for all feasible parameters, including climate sensitivity and CO_2 concentration stabilization levels (see, for example, Schneider [1997]).

3. Varying the Present-Day Overturning Rate

Just as comprehensive climate models have different sensitivities to CO_2 increase, they also have varying rates of thermohaline overturning circulation in their unperturbed, present-day “control” cases (Rahmstorf [1999]). Scientists are uncomfortably uncertain about the detailed geographic locations and even the overall average strength of the present day overturning. Current comprehensive models produce “control” circulations varying from 10 Sv to over 40 Sv in the average strength of overturning. It seems plausible that a model with a stronger present-day circulation would be less prone to a circulation collapse than one having a weak present-day circulation since the stronger the initial circulation, the more flexibility it has to change before reaching the instability point. By analogy, if an object were left on a table that was often getting bumped, the object would be more likely to fall off if it started out closer to the edge of the table than to the middle. To test this hypothesis, the SCD model was adjusted to create a "strong" control case having 40 Sv of overturning and a "weak" control case having only 10 Sv. All else was kept the same. The 750 ppmv CO_2 stabilization scenario was then run for the four climate sensitivities of 1.5 ºC, 2.25 ºC, 3.0 ºC, and 4.5 ºC per CO_2 doubling.

As conjectured, the "strong" overturning model version does not show a collapse even for the highest climate sensitivity (4.5 ºC), but the "weak" version shows a collapse for both the 4.5 ºC and 3.0 ºC climate sensitivity cases.

This result indicates that the modeler's assumption regarding the present day overturning rate is probably an important factor in the model's sensitivity to thermohaline collapse (e.g., Rahmstorf [1999]). Variation in the assumed initial overturning rate, combined with variations in the model's climate sensitivity, probably explains much of the differences in sensitivity to thermohaline collapse found among models. Furthermore, there is yet a third geophysical process that introduces further uncertainty, but which we have not considered in the SCD: hydrological sensitivity (see Rahmstorf and Ganopolski [1999]), which is the amount of fresh water transported via the atmosphere to the North Atlantic from water that evaporated in more tropical latitudes as a result of the world warming.

4. Varying the Rate of Increase in the Concentration of CO_2 in the Atmosphere

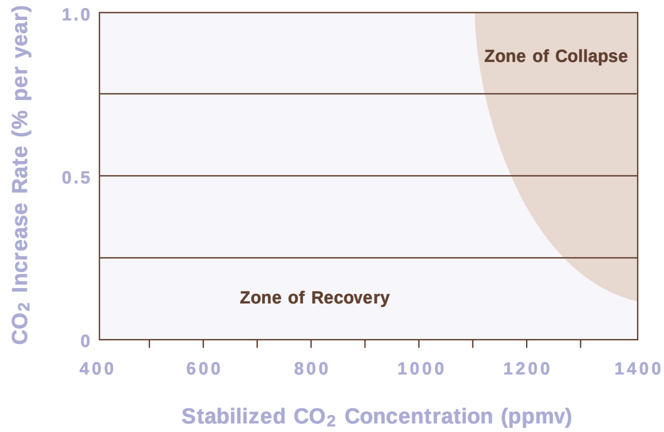
Some models show that the rate of increase of CO_2, not just the absolute amount, can influence thermohaline collapse (e.g., Stocker and Schmittner [1997]). The reason that the rate matters is that the northern ocean can rid itself of lower density surface water by pumping it into the deep ocean, thus effectively diluting the perturbation, but only if the density perturbation is slow enough. That is, if the ocean is disturbed suddenly by freshwater input or rapid warming, there is less time for the less salty or warmer water to mix with the rest of the ocean water than is the case for slow disturbances. Thus, the sudden disturbance will have more impact on the reduction of overturning than a more slowly building disturbance, even if both disturbances eventually represent the same cumulative amount of fresh water injection.

Earlier it was noted that there are two opposing feedback effects when the circulation weakens: a stabilizing (negative feedback) thermal effect and a destabilizing (positive feedback) haline (salt) effect.

If the forcing on the system is rapid enough, it appears that the positive feedback dominates and the catastrophe is more probable. That is, if temperature or fresh water input increases too rapidly, the overturning circulation collapses. However, Stouffer and Manabe (1999) found that if CO_2 is stabilized at a doubling of the present concentration (thereby preventing the total collapse of the circulation), the long-term amount of circulation weakening can actually be larger in cases of slow CO_2 buildup than in cases of rapid CO_2 buildup. This is because when CO_2 buildup is faster, even though the ocean circulation weakens more rapidly initially, the climate system is exposed for a longer period of time to CO_2 forcing in the slow doubling case. The key issue is not just the rate of buildup, but whether the stabilized CO_2 concentration, combined with the rate of increase in concentration, causes a total collapse of the circulation. In the case of a total collapse, even a return to present concentrations might not return the circulation to present-day conditions.

Figure 6

The Ocean Circulation **Zone of Collapse**



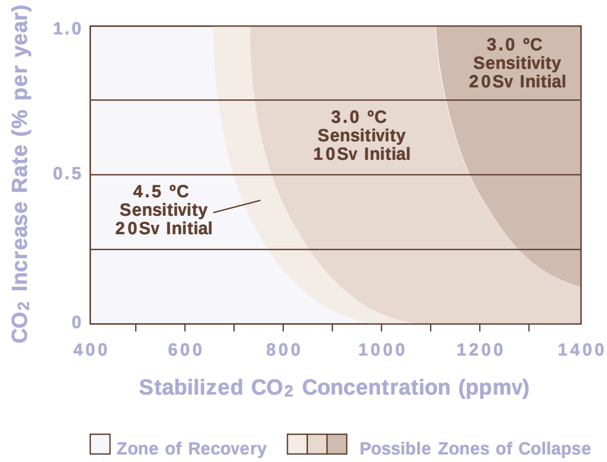
Note: The strength of the thermohaline overturning circulation is shown as a function of the stabilized CO_2 concentration and CO_2 annual increase rate. All runs start from an equilibrated pre-industrial state, follow the historical CO_2 increase, and then follow the path defined by the given increase rate and stabilization value. The model climate sensitivity is set at 3.0 ºC for a CO_2 doubling. Note the permanent thermohaline circulation collapse ("Zone of Collapse") for a combination of sufficiently high stabilized CO_2 and CO_2 increase rate.

Figure 6 shows a plot of the behavior of the thermohaline circulation after it is allowed to reach its equilibrium many centuries in the future as a function of both stabilized CO_2 concentrations and the annual rate of increase of CO_2 prior to stabilization. A mid-value of climate sensitivity of 3.0 ºC per CO_2 doubling was used. Each of the 420 SCD model simulations that comprise the figure was run for 10,000 years to eliminate temporary reductions in the thermohaline circulation. In this case the important question is whether the circulation collapses permanently or recovers. As can be seen on Figure 6, the stability of the circulation does depend on the rate of CO_2 increase as well as the stabilized CO_2 concentration. For a CO_2 increase rate of 0.9 percent per year, the circulation collapses at 1125 ppmv. However, a stabilized concentration of 1450 ppmv can be reached without collapsing the circulation, if the CO_2 increase rate is only 0.2 percent per year. (Recall that the current rate of increase in the CO_2 concentration is 0.6 percent per year.)

Increasing the climate sensitivity or decreasing the initial amount of overturning both act to increase the likelihood that the model's overturning circulation will collapse. This is illustrated in Figure 7, which shows how the "Zone of Collapse" enlarges. It is important to observe that the location of the dividing line between the "Collapse" and "Recovery" zones is determined by two uncertain socio-economic factors (CO_2 stabilization value and CO_2 rate of increase) and two uncertain geophysical factors (climate sensitivity and present-day ocean overturning circulation strength), and that no one is yet able to confidently place a "You Are Here" marker on this particular chart.

Figure 7

Uncertainty in the **Zone of Collapse**



Note: The dividing line between circulation recovery ("Zone of Recovery") and permanent collapse ("Possible Zones of Collapse") depends not only on the geopolitical factors of stabilized CO_2 concentration and CO_2 increase rate, but on the uncertain geophysical factors of global climate sensitivity and present-day (initial) ocean circulation overturning rate.

These calculations are not meant to be taken literally given the high degree of simplification in the model relative to the rich set of non-linear behaviors the model shows are plausible. However, even this simple model demonstrates that complex properties of the coupled climate-economy system must be taken into account, even if the specific numbers here are just illustrative. The complexity of the system gives rise not only to large uncertainties but also to abrupt and potentially major climatic changes. This cannot be ignored by rational analysis, and is the reason to explore these possibilities with quantitative models even if specific results are not definitive.

F. Policy Implications

As noted earlier, most conventional climate-economy models used for climate policy analysis assume either fixed changes in climate forcing (e.g., a doubling of CO_2), or smoothly varying climate change scenarios (e.g., 0.2 °C warming per decade). This paper reiterates that the climate system is non-linear, which means that thresholds may exist at certain stages in the evolution of climatic changes. At these thresholds, a smoothly varying disturbance, such as a GHG buildup, may trigger a rapid event or events. Most analysts who attempt to project the damage that climate change might bring to the environment or to society argue that human capacity to adapt can ameliorate such damages (e.g., Mendelsohn et al. [2000]). However, those analysts typically assume either fixed or smoothly varying climate scenarios. In the case of rapid climate changes, adaptive agents would have neither the knowledge of impending warming, nor the time to marshal the resources to adapt (e.g., Schneider, Easterling, and Mearns [2000]). Thus, it is likely that most analysts using smoothly varying climate changes have overestimated human capacity to adapt to rapid climate changes. Also, natural systems rarely can adapt, without losses, to rapid changes. Thus a new generation of IAMs is needed to explore the implications of rapid climate changes on managed and unmanaged systems.

Moreover, modest climate policies that may be "optimal" for smoothly varying climate change scenarios in which adaptation plays a major role may not make sense in a rapidly changing world. Much more may be at stake in reducing the rate at which humans disturb the climatic system than may be inferred from studies that assume smoothly varying scenarios — e.g., DICE and an entire generation of conventional climate-economy optimization models. The present study clearly demonstrates that a great deal of caution needs to accompany most conventional climate policy analyses in which the only cases analyzed are perfectly foreseen and smoothly increasing temperatures.

G. Conclusions

The authors have produced a simple, portable, and efficient climate model that reproduces some of the important behaviors of the comprehensive, coupled ocean-atmosphere models that currently serve as the standards for global climate research. In particular, the Atlantic overturning circulation in the simplified model and the comprehensive models responds similarly — both qualitatively and quantitatively — to time-dependent global warming forcing. This is true for both temporary reductions in the overturning circulation and for total circulation collapse. The simplicity of the model allows it to clearly distinguish the roles of four uncertain parameters in controlling an overturning collapse: (1) the CO_2 stabilization concentration, (2) the rate of increase in the CO_2 concentration, (3) the global climate sensitivity, and (4) the initial overturning circulation strength. The first two are primarily driven by socio-economic factors, controlled by human population, affluence, energy efficiency, and the technologies used to produce energy or sequester carbon. These socio-economic factors can be manipulated by the kinds of climate policies that fill the current literature and are featured in political debates. The second two factors are geophysical properties of the climate system. Although much is known about them, they still are best characterized by subjective probability distributions that allow a rather wide range of values. This range encompasses the possibilities that the conveyor belt circulation could be either highly stable or easily pushed to a catastrophic collapse. Moreover, it could take decades of empirical and theoretical research to narrow the range significantly (see e.g., IPCC Third Assessment Report, in preparation). There is a possibility that decisions made over the next few decades about GHG emission trajectories over the next century could cause an irreversible drift towards the collapse of the circulation — an event that would become part of the legacy of the twenty-first century policy-makers to the citizens and ecosystems of the twenty-second century and beyond.

The actual dependence of climate change on the rate at which GHGs are allowed to build up stands in contrast to the standard assumptions in most IAMs for which only the stabilization level matters, not the rate at which stabilization is achieved. This disconnect could have a marked impact on the “timing debate” (e.g., Wigley, Richels, and Edmonds [1996]) in which some argue that delayed abatement is preferable because early abatement is too costly. If the rate of GHG buildup in the nearer-term could trigger non-linearities appearing only later on in the climate system, then early abatement may be preferable (see e.g., Schneider [1997]).

Apart from its ability to emulate circulation response in a physically plausible way, the model described here is just a traditional, low-resolution, energy-balance climate model. The model is simple enough to be transparent to climate analysts but has enough adjustable parameters to mimic a range of behaviors of more sophisticated models — which can be relatively opaque to all but a few climate modelers. Given that the SCD's range of behavior is more extensive than older simple climate models, it should prove enlightening to couple this new model to economic models of similar complexity. Preliminary analyses (Mastrandrea and Schneider, in preparation) in which the SCD model presented here is coupled to the DICE model show that near-term emissions could trigger abrupt climate changes in the twenty-second century. Thus, agents with infinite foresight would adjust their current optimal CO_2 emissions control rates based on the potential severity of these far-off abrupt changes. Of course, very high discount rates cause little additional near-term policy response from twenty-second century thermohaline collapse relative to lower discount rates, yet the choice of discount rate is not only a technical option, but also a normative judgment about the value of present versus future interests.

Most conventional energy-economy models are based on smoothly varying scenarios; they do not consider rapid changes or threshold events. They likely overestimate the capacity of humans to adapt to climatic change and underestimate the optimal control rate for GHG emissions. It is critical that the full range of plausible climatic states becomes part of climate policy analysis. Indeed, to ignore the implications of rapid, non-linear climatic changes or surprises would lead to inadequate responses to the advent or prospect of climatic changes.

Endnotes

1. Parameters are the specific numerical values used in the models.

2. Sequestration means storing carbon, for example, by planting trees, changing agricultural practices, or through yet-to-be perfected techniques such as burial of carbon in deep geological caverns or at the ocean bottom.

3. Equilibrium is the situation in which the CO_2 concentration stabilizes, the climate change has gone through its transient phase, and a new steady state is achieved.

References

Broecker, W.S. 1991. "The Great Ocean Conveyor." *Oceanography* 4: 79-89.

Broecker, W.S., D.M. Peteet, and D. Rind. 1985. "Does the Ocean-Atmosphere System Have More Than One Stable Mode of Operation?" *Nature* 315: 21-26.

Hoffert, M.I., K. Caldeira, A.K. Jain, L.D.D. Harvey, E.F. Haites, S.D. Potter, M.E. Schlesinger, S.H. Schneider, R.G. Watts, T.M.L. Wigley, and D.J. Wuebbles. 1998. "Energy Implications of Future Stabilization of Atmospheric CO_2 Content." *Nature* 395: 881-884.

Houghton, J.T., L.G. Meira Filho, B.A. Callandar, N. Harris, A. Kattenberg, and M.K., eds., Climate Change 1995, *The Science of Climate Change* (Cambridge, UK: Intergovernmental Panel on Climate Change, Cambridge University Press, 1996).

Manabe, S., and R.J. Stouffer. 1988. Two Stable Equilibria of a Coupled Ocean-Atmosphere Model. *Journal of Climate* 1: 841-866.

Mendelsohn, R, W. Morrison, M. Schlesinger, N. Andronova 2000. "Country-Specific Market Impacts of Climate Change." *Climatic Change* 45(4-5): 553-569

Morgan, M.G., and D.W. Keith. 1995. "Subjective Judgments by Climate Experts." *Environmental Science and Technology* 29: 468A-476A.

Nordhaus, W.D. 1992. "An Optimal Transition Path for Controlling Greenhouse Gases." *Science* 258: 1315-1319.

Rahmstorf, S. 1995. "Bifurcations of the Atlantic Thermohaline Circulation in Response to Changes in the Hydrological Cycle." *Nature* 378: 145-149.

Rahmstorf, S. 1999. "Shifting Seas in the Greenhouse?" *Nature* 399: 523-524.

Rahmstorf, S., and A. Ganopolski. 1999. "Long-term Global Warming Scenarios Computed With an Efficient Coupled Climate Model." *Climatic Change* 43: 353-67.

Roughgarden, T., and S.H. Schneider. 1999. "Climate Change Policy: Quantifying Uncertainties for Damages and Optimal Carbon Taxes." *Energy Policy* 27(7): 415-429.

Schneider, S.H. 1997. "Integrated Assessment Modeling of Global Climate Change: Transparent Rational Tool for Policy Making or Opaque Screen Hiding Value-laden Assumptions?" *Environmental Modeling and Assessment* 2: 229-249.

Schneider, S.H. and S.L. Thompson. 1981. "Atmospheric CO_2 and Climate: Importance of the Transient Response." *Journal of Geophysical Research* 86: 3135-3147.

Schneider, S.H., D.M. Peteet, and G.R. North. 1987. "A Climate Model Intercomparison for the Younger Dryas and its Implications for Paleoclimatic Data Collection." In *Abrupt Climatic Change*. W.H. Berger and L.Labeyrie, eds. NATO/NSF Workshop, Biviers (Grenoble), Reidel, Dordrecht.

Schneider, S.H., W.E. Easterling, and L.O. Mearns. (2000). "Adaptation: Sensitivity to Natural Variability, Agent Assumptions and Dynamic Climate Changes." *Climatic Change* 45(1): 203-221.

Seidov, D., and M. Maslin. 1999. "North Atlantic Deep Water Circulation Collapse During Heinrich Events." *Geology* 27: 23-26.

Stocker, T.F., and A. Schmittner. 1997. "Influence of CO_2 Emission Rates on the Stability of the Thermohaline Circulation." *Nature* 388: 862-865.

Stouffer, R.J., and S. Manabe. 1999. "Response of a coupled ocean-atmosphere model to increasing atmospheric CO_2: sensitivity to the rate of increase." *Journal of Climate* 12: 2224-2237.

Washington, W.M., and C.L. Parkinson. *An Introduction to Three-Dimensional Climate Modeling*. (Mill Valley, CA: University Science Books, 1986).

Wigley, T.M.L., R. Richels, and J.A. Edmonds. 1996. "Economic and Environmental Choices in the Stabilizations of Atmospheric CO_2 Concentrations." *Nature* 379: 240-243.

Appendix: Simple Climate Demonstrator Model Description

The SCD model represents the world as five boxes in the Northern Hemisphere (Figure 2). In fact, only three Atlantic Ocean boxes are required to produce a description of the north Atlantic overturning circulation. However, the additional two boxes represent the “non-Atlantic” remainder of the Northern Hemisphere. These additional boxes allow for east-west gradients and thus allow the simulated variables in each box to bear some quantitative resemblance to real world values, as opposed to being a more qualitative representation of an idealized system. Even more realism could be added by extending the model to have a southern hemispheric component or by sub-dividing the boxes into land and oceanic domains. However, the more complex the system, the less easily can it be coupled to economic models for repeated runs.

The boxes of the SCD model are connected by flows of thermal energy and freshwater (or salinity). An advective (i.e., flowing horizontally between boxes) thermohaline overturning circulation connects the three ocean boxes. All other transports of heat, freshwater or salinity occur by simple “down-gradient” (i.e., from higher to lower values) linear diffusion with coefficients chosen to produce an acceptable control climate. Solar radiative heating and outgoing infrared radiative cooling are handled in the manner of numerous simple energy balance climate models (e.g., Schneider and Thompson, 1981). Outgoing infrared radiation (heat) is a linear function of the surface temperature. The proportionality factor can be adjusted within limits to control the model's overall temperature sensitivity to changes in radiative heating (i.e., to adjust the climate sensitivity of the model). The model includes a traditional snow-ice albedo (surface reflectivity) feedback that linearly increases planetary albedo as a function of decreasing temperature. This is effective only below a threshold temperature. In the simulations discussed in this report the albedo feedback (i.e., the warming-induced melting of snow or ice which enhances the warming by decreasing the albedo) only operates in the northern surface boxes because that is where the bulk of the landmasses are located. The effect of CO_2 as a GHG is added as a radiative heating logarithmically proportional to CO_2 amount. In other words, additional increments of CO_2 yield diminishing returns, as has been known for decades and included in all climate models since the 1960s.

Water is assumed to evaporate from the surface ocean boxes at a rate proportional to the saturation vapor pressure (the amount of water vapor the air can hold before condensation occurs). Thus, evaporation is a non-linear function of temperature only. Water vapor is moved down gradient from the warmer southern ocean box to the cooler northern ocean box and precipitated, producing a positive difference of precipitation minus evaporation (P-E) in the northern box, as is observed in the actual climate system. The poleward transport of water vapor is adjusted to make the P-E values comparable to observed estimates. There is no evaporation, precipitation or runoff in the "non-Atlantic" surface boxes.

The seawater density in the three ocean boxes is determined by an equation of state that is linearized in both temperature and salinity. The strength of the thermohaline circulation is assumed to be linearly proportional to the density difference between the northern surface ocean and the deep ocean. The modeler adjusts the proportionality constant to achieve the desired circulation strength.

The various parameters of the model were chosen to produce a control state similar to that observed in the present day. In particular, the strength of the thermohaline overturning was set arbitrarily at 20 Sv (1 Sv = 1 Sverdrup, defined as one million cubic meters per second). The strength of the albedo feedback was adjusted so that the model's normal climate sensitivity to CO_2-doubling increased from 2.2 ºC per CO_2 doubling without albedo feedback to 3.0 ºC with albedo feedback. The control case equilibrium was derived by running the model for 20,000 years with a pre-industrial atmospheric CO_2 value of 280 parts per million (ppmv).

Temperatures in the control case are 16 ºC for the global surface mean, 6 ºC for the northern surface Atlantic box and 6.5 ºC for the deep ocean. The deep ocean is warmer than observed because the low spatial resolution of the model precludes the deep-water formation in cold spots of limited area that occurs in reality. Tuning the model to make the deep water colder would not affect the model's qualitative behavior, but would result in an unreasonably cold overall northern ocean surface temperature.