The Economics of Climate Policy

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Abstract

Economics has played an increasingly important role in shaping policy, in the United States and elsewhere. This paper reviews some of the dimensions of the economic approach to analyzing, understanding, and developing solutions to the problem of climate change. We then turn to the issue of designing regulatory instruments to control the problem. The paper concludes with a discussion of the political economy of greenhouse gas control in an international context.

Key Words: climate change, climate policy design, integrated assessment, environmental policy coordination

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I.Introduction

One of the biggest environmental issues of the past decade is global warming or, more generally, climate change brought about by human activities, including emissions of various "greenhouse gases" (GHGs). Economics has played a visible role in climate policy debates in the United States and elsewhere, a more prominent role than it has played in some other environmental problems.

This paper serves as a review of some of the dimensions of the economic approach to analyzing, understanding, and developing solutions to the problem of climate change.[1] Much has been written on this subject; consequently, this review can only highlight some of the important results in the literature.

In the next section, we discuss the climate change problem generally, particularly the physical and technological dimensions of the problem and its solutions. In section III we review estimates of the costs and benefits of controlling the emissions of pollution leading to climate change. We then turn to the fundamental economics of the problem in Section IV, laying out a simple analytic model that captures the economic approach to the problem. In section V we address the design of climate policy instruments, after which we turn to the problem of forging viable international climate agreements in section VI.

II.Overview of the Climate Change Issue

In this section we first provide a brief introduction to the science of climate change, addressing both changes in the earth's atmosphere and climate system and the potential consequences of those changes. We then review the different options available for responding to

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[1] Our review draws in part on the material in Shogren and Toman (2000).

the risks posed by climate change. We conclude this section with a brief history of international activities to mitigate the threats.

A. Nature of the Challenge

The composition of the earth's atmosphere—in particular, the natural presence of carbon dioxide (CO_2) and water vapor—causes it to trap heat like a greenhouse. The composition of the atmosphere ensures that the earth is warmer than Mars, but not like Venus.

Human activities add to the concentration of heat-trapping gases in the atmosphere. CO_2 released from use of fossil fuels (coal, oil, and natural gas) is the most plentiful human-created GHG. Other GHGs—including methane (CH_4),[2] the now-banned chlorofluorocarbons (CFCs) and their substitutes currently in use, and nitrous oxides associated with fertilizer use—are emitted in lower volumes than CO_2 but trap more heat per unit of the gas. Other pollutants can enhance or blunt the greenhouse effect. For example, sulfur dioxide emissions lead to sulfate aerosols that cause cooling; ground-level ozone can enhance warming.

Scientists worry that the accumulation of these gases in the atmosphere has and will continue to change the climate.[3] Climate change is a historical fact, as illustrated by the many ice ages. Part of the controversy today is the extent to which human activities are responsible for changes in the climate system. While acknowledging the many uncertainties about the precise nature and strength of the link between human activities and climate change, most climate scientists argue that the evidence points to an effect from people emitting into the atmosphere too much CO_2 and other GHGs.[4]

They reach this conclusion in part by observing two trends. Global-surface temperature data show that the Earth has warmed 0.6ºC (or 1ºF) over the past 100 years. At the same time,

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[2] Human-induced methane releases come from natural gas supply leaks, some coal mines, decomposition in landfills, and agricultural sources such as rice paddies and domestic animals.

[3] Climate change is not the same as the day-to-day or even year-to-year fluctuations of the weather. However, the nature of these fluctuations is one of the things that could be altered by climate change.

[4] The first volume of the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 1996a) provides a good summary of the state of knowledge on climate change as of the early 1990s. (The IPCC is a group of physical, biological, and social scientists convened by the U.N. Environment Programme and the World Meteorological Organization to assess the state of existing knowledge about climate change and its impacts.) Since the Second Assessment Report there has been a huge amount of continued scientific inquiry about the processes of climate change. The IPCC is scheduled to issue its Third Assessment Report in 2001.

atmospheric concentrations of GHGs like CO_2 have increased by about 30% over the past 200 years, basically since the beginning of the industrial revolution. Scientists attempt to capture the interactions of a complex dynamic climate system and the human activities that put additional GHGs in the atmosphere by developing complicated computer models. These models simulate how future climate conditions might change with, for example, a doubling of the preindustrial concentration of GHGs in the atmosphere.

Some scientists stress that one should not confuse correlation with causation. These scientists also question the current ability to separate human-induced changes from natural variability. While the causation between human actions and higher temperatures continues to be debated, the Intergovernmental Panel on Climate Change (IPCC) concluded in its Second Assessment Report that "…the balance of evidence suggests that there is a discernible human influence on global climate."[5] The recently released summary of the IPCC Third Assessment Report concludes that "there is new and stronger evidence that most of the warming observed over the last fifty years is attributable to human activities" (IPCC, 2001; p 10). A recent report by the U.S. National Research Council (2000) states that evidence for a human contribution is rising. At the same time, however, the report showed a wide range of possible quantitative forecasts of climate change.[6]

Greenhouse gases remain in the atmosphere for decades to hundreds of years, depending on the gas. Concentrations of GHGs depend on the long-term profile of emissions; changes in emissions in any one year have a trivial effect on overall concentration levels. Even significant reductions in emissions made today would not substantially affect concentrations for decades or longer. In addition, the major emitters of GHGs will change over time. Today the industrialized world accounts for the largest portion of emissions. By the middle of this century, however, developing countries with growing population and wealth are likely to generate the largest share of emissions, given their rising populations and economic activities. Both of these factors affect how one designs climate policies, as we discuss below.

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[5] The phrase "balance of the evidence" is taken from the policymakers' summary of the IPCC (1996a) report and has generated some controversy in its own right. Chapter 8 of the report characterizes the many uncertainties.

[6] Particularly vexing is the limited ability of physical models to capture (i) climate change on any scale less than continental, making it difficult to assess regional changes; (ii) how conventional pollutants such as very fine "aerosol" particles are offset by the effect of GHGs by reflecting back sunlight; and (iii) how human activity on land can create "carbon sinks", sequestering GHGs in biomass, for example, reforestation, soil banks.

B. The Potential Physical and Socioeconomic Consequences of Climate Change

The risk of climate change depends not just on what happens to the climate system but also on the physical and socioeconomic implications of a changing climate. Climate change might have a variety of effects. Examples include:

- Reduced productivity of resources that humans use or extract from the natural environment, such as lower agricultural yields and timber harvests and scarcer water resources.
- Damage to human-built environments, such as coastal flooding from sea-level rise, incursion of salt water into drinking water systems, and damages from increased storms and floods.
- Risks to life and limb, such as more deaths from heat waves and increased incidence of tropical diseases as these diseases migrate to formerly more temperate climates.
- Damage to "less managed resources", such as wilderness areas, natural habitats for scarce species, or biodiversity. Sea-level rise, for example, would inundate coastal wetlands, whereas increased inland aridity could destroy prairie wetlands.

All of these damages are posited to result from long-term changes in the concentrations of GHGs in the atmosphere, as well as very rapid rates of climate change. Most of the adverse effects of climate change most likely will take decades or longer to materialize. Moreover, the odds that these events will come to pass are uncertain and not well understood. Numerical estimates of physical impacts remain scanty, and confidence intervals are even harder to delineate. Sea-level rise from polar ice melting, for instance, is perhaps the best understood, and the current predicted range of change is still broad.[7] The risks of catastrophic effects such as shifts in the Gulf Stream or the sudden collapse of polar ice caps are even harder to gauge.

Unknown physical risks are compounded by uncertain socioeconomic consequences. Estimates of potential impacts on market goods and services such as agricultural output can be

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[7] Scenarios presented in IPCC (1996a) indicate possible increases in sea level by 2100 of less than 20 cm to almost 100 cm from a doubling of the atmospheric greenhouse gas concentration. This presentation partly reflects uncertainty about how temperature will respond to increased GHGs, and partly how oceans and ice caps will respond to temperature change.

made to some degree, at least in developed countries. But monetary estimates for nonmarket goods such as human and ecosystem health give rise to serious debate.[8]

Much of the climate change debate focuses on the long-term implications of a changed climate. Less of the debate considers the pace of climate change.[9] To illustrate the point, suppose human systems are exceedingly resilient and, given enough time, can completely adapt to any change in the climate. The changes that are necessary to adapt as the climate changes may nonetheless be very costly. If Manhattan Island is flooded, eventually New York City will relocate further inland, and, if we revisit it in a millennium or two, it is possible that the citizens of New York will have completely adapted. Yet clearly the consequences of rapidly flooding Manhattan Island are enormous.

Moreover, existing estimates of risk apply almost exclusively to industrial countries like the United States. Less is known about the adverse socioeconomic consequences for poorer societies, even though these societies arguably are more vulnerable to climate change. Economic growth will presumably lessen some of the vulnerability to climate change, for example, threats to agricultural yields or basic sanitation services. However, economic growth in the long term would be imperiled in those areas (like tropical and coastal regions) dependent on natural and ecological resources adversely affected by climate change. Aggregate statistics mask considerable regional variation, with some areas likely to benefit from climate change while others lose.[10] In weighing the consequences of climate change, moreover, it is also important to keep in mind that humans adapt to risks that they perceive so as to lower their losses. We return to this point below.

Policymakers must address hazy estimates of risks, benefits from taking action, and the potential for adaptation against the uncertain but also consequential cost of reducing GHGs when constructing a viable and effective risk-reducing climate policy. Costs of mitigation matter, as do costs of climate change itself. One must consider the consequences of committing resources to reducing risk of climate change, resources that could otherwise be used to meet other human interests, just as one must weigh the consequences of different climatic changes.

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[8] See Moore (1998), Tol (1995), Nordhaus and Boyer (2000), Faskhauser (1995), and Mendelsohn and Neumann (1999).

[9] See Fankhauser and Tol (1996) and Schneider and Kuntz-Duriseti (2001).

[10] IPCC (1998) provides a review of the current state of knowledge on regional impacts. See also Norhaus and Boyer (2000), Nordhaus and Yang (1996) and Tol (1995).

C. Mitigation and Adaptation

There are of course many things that can be done to "manage" the climate change problem. Some of these actions are best done by governments, such as mandating emission reductions or investing in more resilient infrastructure. Other actions are best done by private agents acting on their own, such as adapting production practices to a different climate. In fact, there is great richness in the types of things that can be done to reduce the deleterious effects of climate change. In this section, we consider four categories of actions: emissions control, carbon sequestration, geoengineering, and adaptation.[11]

As we saw above, climate change can involve a myriad of effects, ranging from changed mean temperatures and precipitation, changed variance of the weather (more or less frequent storms), and sea-level change, to more subtle effects such as incursions of pests and disease, particularly insect pests whose territory changes (for example, the Anopheles mosquito, carrying malaria). How climate change is manifested is obviously important to how we characterize such aspects as adaptation and mitigation.

1. Emissions Control

The most obvious way of managing climate change is to reduce emissions of GHGs into the atmosphere, particularly CO_2 from fossil fuel combustion. Technologically, this objective involves either reducing use of carbon-rich fuels or using technology to reduce emissions of GHGs from what otherwise would be the case, in much the same way that precipitators remove particulates from smoke streams. Removal of GHGs from emissions streams is technically feasible, and there is increasing interest in this technological option for managing climate change in the longer term (Kim and Edmonds 2000, McFarland et al. 2001). These options are still quite expensive (in terms of overall cost, including reduced energy output) compared with other options; there are questions about the long-term permanence of some CO_2 storage approaches; and the technologies in question are most readily applicable to large stationary emission sources,

[11] There are other ways of categorizing steps to manage climate change. NAS (1992) divides actions temporally into mitigation, which seeks to arrest the problem before it occurs, and adaptation, which seeks to reduce the negative impacts of climate change. The IPCC (1996b) does not distinguish between adaptation and adjustment, instead defining adaptability as the extent to which adjustments are possible. Of course it is the concepts that are important, not the semantics.

which represent only a fraction of total greenhouse gas emissions. Nevertheless, these technologies are moving from the realm of fantasy to the realm of the technologically possible and the economically imaginable.

Widespread availability of environmentally sound and economically affordable engineered sequestration would fundamentally change the nature of the climate policy debate by relaxing the current tight link between carbon policy and reduced use of fossil fuels. It would also fundamentally alter the economic analysis of climate policy by creating a new kind of "backstop technology." Instead of considering only non-fossil energy technologies that become economic over the long term after a high shadow price is put on GHG emissions, it might be possible for fossil fuels to continue being utilized extensively with a more modest shadow price that induces end-of pipe treatment.[12] Nevertheless, over the short-to-medium term this approach is not likely to be that significant compared to reducing the use of carbon-rich fuels. And there is no assurance these technologies will developed as hoped in terms of cost or environmental reliability.

Emissions control generally must be mandated by the government, which is not the case for some of the other risk mitigation and adaptation strategies. Governments must provide requirements and/or incentives for individuals, firms, and public agencies to reduce GHG emissions and perhaps pursue strategies to reduce the cost of controlling GHG emissions. Later in this paper we will address the menu of policies that are available to accomplish this goal.

2. Sequestration

Although restricting the emissions of GHGs into the atmosphere is an important goal, the atmosphere already has significant quantities of GHGs, particularly CO_2. Another strategy for managing the GHG problem is to store CO_2 (or simply carbon) that is currently in the atmosphere somewhere besides the atmosphere. This practice is sequestration.[13]

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[12] Kim and Edmonds (2000) cite figures based on technology research byu the US Energy Department indicating that while current costs are well over $100 per ton of carbon captured, and may run over $300 per ton for some technologies, there is an aspiration to bring these costs down to around $10 per ton in a relatively short time (the next 25 years). This would reduce the shadow prices necessary to stabilize atmospheric CO_2 concentrations by over 70 percent relative to scenarios without such technoligies.

[13] In some uses, "sequestration" is interpreted to include extraction and storage of GHGs from waste gas streams (which we mentioned above under emissions control) as well as biological storage, which is our focus here.

The most common and obvious form of sequestration is carbon stored in plants, particularly trees (Sedjo et al. 1997; Stavins 1999; Sedjo and Sohngen 2000; Newell and Stavins, 2000). There are problems with sequestration in trees. Forests around the world are being cleared, effectively releasing previously stored carbon into the atmosphere.[14] Land is becoming scarcer due to population pressures, and sequestration in trees requires land. Another problem is that sequestration of new carbon slows significantly when a tree reaches maturity. Thus there is a limit to how much carbon can be sequestered simply by planting trees. Some researchers have addressed this question by proposing the “pickling” of cut trees, possibly storing them in the cold deep ocean (Nordhaus, 1991). Another problem with sequestration is that it can easily be reversed and that is not always easy to detect. A forest that has been used to store carbon can be logged rapidly, or burn, reversing the sequestration. For this reason, some advocates of GHG reduction are nervous about relying on sequestration as a control measure.

There are other places to sequester carbon besides trees. Different agricultural practices can increase the storage of carbon in the soil through the plant roots. Like mitigation, sequestration involves the active involvement of government. Sequestration beyond “business as usual” trends will not be pursued without government incentives or direction.

3. Geoengineering

Geoengineering is the province of “big thinkers.” Rather than controlling the concentration of GHGs in the atmosphere, geoengineering would undertake large-scale engineering of our environment to reduce the impacts of climate change directly. The menu of possibilities is lengthy.[15]

Several geoengineering approaches have been proposed to reduce the level of climate change, in particular by increasing the reflectivity (albedo) of the earth. As described in NAS (1992), there are many schemes for achieving this objective, including adding dust to the stratosphere, adding mirrors to space just outside the atmosphere, floating large balloons high in the atmosphere, and painting the roofs of houses white.

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[14] When a tree is cut, the carbon in the tree is not of course immediately released to the atmosphere. This release requires either combustion of the wood or decomposition.

[15] See Marland (1996), Schneider (1996) and Schelling (1996).

A good deal of CO_2 (and other gases) is dissolved in the ocean. Small ocean creatures (phytoplankton) incorporate carbon into their skeletons and shells, which are subsequently deposited on the ocean floor. In principle this potential could be exploited by encouraging the growth of these ocean microorganisms by "fertilizing" the ocean with other necessary nutrients like trace quantities of iron, which stimulates photosynthesis and thus phytoplankton growth (NAS 1992). However, the consequences of this approach for marine ecology are unclear.

Few of these ideas appear feasible at present, though they do remain options. Even more than mitigation and sequestration, geoengineering would require major public policy efforts.

4. Adaptation

The three approaches that have just been discussed, emission control, sequestration, and geoengineering, have focused on the public-good nature of the global climate and thus of necessity have they been activities initiated by governments as public-goods providers. We now turn to actions that individual agents as well as governments take to reduce the impact of climate change.

Farmers clearly can and will change their practices when they observe or anticipate the climate changing. Agriculture thrives in many climates around the world and does not need climate homogeneity. Thus, one could consider a climate change in one location as equivalent to the climate there becoming like another spot on earth, whose agricultural practices ultimately will be adopted. This observation is the essence of the Mendelsohn et al. (1994) analysis of the long-term effects of differing climates in the United States on agricultural productivity (via land value).[16]

The subject of farmer adaptation has been researched and discussed at length (see Schimmelpfennig et al. 1996; Rosenberg 1993). Although no consensus exists, the basic conclusion emerging from this literature is that, at a global level and in many regions, agriculture is highly adaptable when growers have the capacity to anticipate and react to prospective changes. This conclusion is underscored by the likelihood of further research to expand adaptation opportunities (for example, more drought-resistant crop types). According to this view, climate change will not pose a significant threat to global food supply. It may pose local

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[16] There is controversy over this approach to inferring adaptation possibilities by comparing locations with different long-run equilibrium climates. See Schneider et al. 2000.

threats, however, especially in the period of transition to an altered climate regime. This threat could be troublesome in some areas, especially in developing countries, where adaptation capacity is more limited and agriculture (both market and subsistence) is a large share of total economic activity.[17]

The adaptation of forest systems to climate change has also received extensive study (see, for example, Sohngen and Mendelsohn 1999). The general message in the economic assessments is that, overall, the impacts on global timber markets over the long term are likely to be modest (taking account of salvage harvesting in the event of die-backs, regeneration of different natural forests, and adaptation through advanced plantation cultivation techniques). As well, the transition costs may be more serious in some areas, and the impacts on nonmarket forest resources—in particular, biodiversity—may be more problematic.

Changing precipitation patterns will create local stresses on water resources. These likely can be adapted to at some cost. The effects will depend on the severity of the local impacts, which remain uncertain, and the degree of adaptation capacity, which could be problematic in some places (again, especially in developing countries; Frederick et al. 1997, Frederick and Gleick, 1999). Adaptation will be blunted by such institutional failures as missing water markets and price subsidies that conceal the true scarcity of water resources.

Less well-known is how easily other sectors of the economy can adapt to climate change. Nordhaus (1994) has suggested that most nonagricultural sectors of developed economies are not particularly dependent on the climate or weather. Mendelsohn's (1999) general survey of climate change vulnerability comes to a similar conclusion. However, this characterization focuses mainly on the consequences of a long-term rise in mean temperature and associated effects. Certainly an increased frequency of devastating weather (for example, hurricanes) can have widespread effect, even to a sector not typically dependent on climate. For instance, the electric power sector can deal very well with changes in mean weather; but storms bring havoc, particularly to distribution and transmission systems.

Natural ecosystems also are affected by climate change and to the extent that humans are affected, tangibly or intangibly, by these ecosystems, we need to be concerned with their ability to adapt. This capacity—for example, in wetlands or wilderness areas—remains quite uncertain.

[17] On adaptation in India and Brazil, see Mendelsohn and Dinar (1999) and the rejoinder by Riley (1999).

Also uncertain are the impacts of climate change on human health (more extreme weather, more tropical diseases) vis-à-vis the capacity to adapt to these impacts.[18]

The costs of adjusting from one climate to another could be significant and they depend particularly on the speed at which the climate changes, as well as on the resilience of the natural systems being affected. We would expect to observe two main types of adjustment as the climate changes. One has to do with agents learning how to deal with a new environment. This adjustment may be easy or difficult, especially if information about adaptation challenges and opportunities is limited. It will be compounded by uncertainty about whether the climate has changed, an issue we return to in a later section. Another effect is associated with adjusting the stock of capital, such as buildings and machinery. Clearly, if the sea around Manhattan rises 1 mm a year, it will be easier to adjust than if the rate of increase is 100 mm a year. In the former case, capital can be allowed to depreciate; whereas in the later case, perfectly good capital will need to be abandoned.

In general, the ability to adapt contributes more to lowering the net risk of climate change in situations where human control over relevant natural systems and infrastructure is greater. We have more capacity to adapt in agricultural activities than in wilderness preservation, for example. The potential to adapt also depends on a society's wealth and on the presence of various kinds of social infrastructure such as educational and public health systems; for example, richer countries are likely to face less of a threat to human health from climate change than poorer societies with less infrastructure.

D. International Policy Toward Climate Change

Table I summarizes some milestones in the evolution of global climate policy. The negotiation of the 1992 Framework Convention on Climate Change was a watershed in that

Table I. Summary of Key Milestones in Climate Policy

1979	First World Climate Conference held in Geneva
1990	First Assessment Report of the Intergovernmental Panel on Climate Change (IPCC); initial evidence that human activities might be affecting climate, but there is significant uncertainty

[18] For further general discussion of adaptation possibilities see Smith et al. 1996, Pielke 1998, Kane and Shogren 2000, and Schneider et al. 2000.

1990	Second World Climate Conference held in Geneva; agreement to negotiate a "framework treaty"
1992	U.N. Framework Convention on Climate Change (UNFCCC) established at the U.N. Conference on Environment and Development (UNCED, the "Earth Summit"), Rio de Janeiro; "Annex I" developed countries pledge to return emissions to 1990 levels by 2000
1995	IPCC Second Assessment Report completed (published in 1996); stronger conviction expressed that human activities could be adversely affecting climate
1995	"Berlin Mandate" developed at the first Conference of Parties (COP1) to the UNFCCC agreement to negotiate legally binding targets and timetables to limit emissions in Annex I countries
1997	COP3, held in Kyoto Japan, led to the "Kyoto Protocol," Annex I/Annex B countries agree to binding emission reductions averaging 5% below 1990 levels by 2008–2012, with "flexibility mechanisms" (including emissions trading) for compliance; no commitments for emission limitation by developing countries
1997	U.S. Senate passes Byrd–Hagel resolution 95–0, stating that the United States should accept no climate agreement that did not demand comparable sacrifices of all participants, and calling for administration to justify any proposed ratification of the Kyoto Protocol with analysis of benefits and costs
1998	COP4, held in Buenos Aires Argentina, emphasizes operationalizing the "flexibility mechanisms" of the Kyoto Protocol; IPCC Third Assessment begins
1999	COP5, held in Bonn Germany, continued emphasis on operationalizing the flexibility mechanisms
2000	COP6 held in the Hague; deadlock on implementing key provisions of the Kyoto Protocol
2001	US President George Bush states opposition to the Kyoto Protocol

Sources: U.N. Environment Programme (www.unep.ch/iucc/fact17.html); Intergovernmental Panel on Climate Change (www.ipcc.ch/activity/act.htm); United Nations Framework Convention on Climate Change Secretariat (www.unfccc.de/text/resource/index.html).

process.[19] Article 2 of the Convention states that the objective is to stabilize concentrations within a time frame that would prevent "dangerous" human damage to the climate system. Article 3 states that precautionary risk reduction should be guided by equity across time and wealth levels, as expressed in the concept of "common but differentiated responsibilities." Article 4 states that nations should cooperate to improve human adaptation and mitigation of climate change through financial support and low-emission technologies. Articles 3 and 4 also refer to the use of cost-effective response measures.

[19] For a text of the Convention and subsequent documents (including the Kyoto Protocol discussed below), see www.unfccc.de.

The 1997 Kyoto Protocol to the Framework Convention is the next major milestone. The Protocol states that the industrialized “Annex B” countries (known in the Convention as “Annex I” countries) agreed to legally binding emissions reductions by the 2008–2012 period, resulting in emissions averaging 5% below 1990 levels.[20] Given expected business-as-usual emissions growth in the United States between 1990 and 2010, the actual emissions reductions needed for compliance are substantial (on the order of one-third of what otherwise would prevail in the United States). No numerical targets for emissions of developing countries were set in the protocol. In other words, the approach taken was “deep, then broad”; a few countries are to make significant cuts early with the hope of broader participation later, rather than the “broad, then deep” strategy promoted by many critics of Kyoto.[21]

The Kyoto Protocol includes several “flexibility” mechanisms that allow nations some latitude as to how they will meet the targets and timetables. The exact details of how these mechanisms would operate were left largely for future negotiations. Individual Annex B countries are free to achieve their targets through any credible domestic policies they wish to use; domestic policies need not be coordinated. The Protocol also provides for international “where flexibility” in which nations can reduce emissions through different forms of international trading of emissions quotas. We discuss these options in more detail in Section V. The Protocol further provides flexibility in that emissions targets can be met by reducing any of six different gases, not just CO_2, as well as through carbon sequestration through “sinks” such as forests. Non-CO_2 gases are compared with CO_2 by means of “global warming potential” equivalency factors that reflect the heat-trapping properties of different gases in the atmosphere.[22]

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[20] Annex I nations were listed in an appendix (Annex I) to the Framework Convention. In the Kyoto Protocol, the list of nations is in Annex B. The targets agreed to in Kyoto varied across countries, with the United States agreeing to a 7% reduction while Western Europe undertook an overall cut of 8% (divided unequally among European Union members in subsequent negotiations) and Japan accepted a less steep reduction of 6%. Special provisions were made in defining the obligations of the industrialized countries of Central and Eastern Europe and the former Soviet Union, whose emissions already are below 1990 levels. The agreement is further complicated by the fact that reductions in a number of other GHGs, not just CO_2, “count”. There is also a role for carbon sequestration in biomass (that is, increased forest cover), but this role has not been made clear yet.

[21] For a critique of the Kyoto Protocol’s “deep then broad” character see Jacoby et al. (1998) and Shogren (1999). We return to this issue in Section VI below.

[22] However, variations in long-term heat-trapping capacity do not immediate translate into variations in potential damage. For example, methane has high heat-trapping potential but a short residence time in the atmosphere compared with CO_2. If damages from climate change are growing over time because of GHG accumulation generally, near-term CH_4 releases will be less consequential than near-term CO_2 releases, whereas the opposite is

Post-Kyoto meetings continued the international debate, especially about the technical, legal, and moral foundations of the proposed flexibility mechanisms. This debate revealed sharp differences in opinion between the United States (with some other energy-intensive industrialized countries) and the European Union, as well as many developing countries. At issue was the extent to which reliance on international emissions trading could substitute for, or could only complement, domestic efforts to reduce energy use and CO_2 emissions. The ultimate fate of the flexibility mechanisms—and of the Protocol itself—remains to be seen.

III.Benefits and Costs of Greenhouse Gas Control

A fundamental building block of a viable climate control policy is a quantitative understanding of the consequences of climate change and emission control. We turn to these issues in this section.

The loss of welfare from a change in the climate can be dealt with in terms of the benefits of GHG control or in terms of the damages from a lack of control and a continuation of emission growth leading to climate change. We refer to benefits rather than damages though the concepts are the same. The costs of GHG control are somewhat more straightforward but still fairly uncertain. Though some say GHG emissions can be reduced substantially, at no cost, simply by eliminating inefficiencies, most analysts recognize that there are costs associated with significantly reducing the emission level.

In this section we examine three questions at a fairly superficial level. The first issue concerns the costs of GHG control. The second issue covers the benefits of GHG control. The third section includes estimates of the net benefits of pursuing control that balances costs and benefits.

A. Costs of Greenhouse Gas Control

true if emissions are occurring near the time of peak climate change and impacts (Reilly and Richards 1993, Schmalensee 1993, Hammitt et al. 1996, Smith and Wigley 2000a, 2000b). Ideally, for policy purposes different GHGs should be traded off against each other based on their relative contribution to socioeconomic impacts, not just their chemical properties; but there is no agreement on what damage-based equivalence factors should be. Uncertainty about the way to discount the streams of long-term socioeconomic impacts is a significant element of this problem.

We first turn to the question of what economic costs might be associated with a reduction of GHG emissions. Though one might ultimately like to aggregate such costs into a marginal cost schedule, indicating the overall incremental cost from specific levels of reduction, it is appropriate to understand the nature of these costs and the difficulty in measuring them.

Imagine a country levying an emission fee of $10 per ton of carbon. How might that country's economy respond to such a fee? If we conduct this thought experiment for a range of such fees, we trace out a marginal control cost schedule.

A range of effects result from ratcheting up the price of carbon, some short-run, some long-run. In the short run, consumers of fossil fuels will reduce use because of the increase in cost of fossil fuel caused by the charge for carbon emissions. Reducing use is not a costless process. Drivers that forego travel have lost utility as a result of the increase in the effective cost of driving. Products that involve GHG emissions as part of the production process will become dearer, and thus sales will be marginally lower. For instance, fertilizer may become more expensive because of the inputs of fossil fuels in its manufacture. This price increase will result in less fertilizer use. In both the case of the driver reducing auto use and the farmer reducing fertilizer use, additional resources are expended in attempting to overcome the increased price of carbon emissions. Drivers lose utility from driving less but may also buy more expensive fuel-efficient cars; farmers may adopt more expensive farming practices to make up for the loss in use of fertilizer. There are direct effects of raising the price of carbon and there are indirect, ultimately general equilibrium, effects of raising the price of carbon.

1. A Cost Taxonomy

Hourcade et al. (1996a) distinguish four types of costs associated with reducing emissions of GHGs: direct outlays for control, partial equilibrium costs to consumers and producers, general equilibrium costs, and nonmarket costs.[23]

Direct outlays for control are the most intuitive and obvious costs of control: scrubbers to remove CO_2, the extra costs of using natural gas instead of coal, the costs of additional insulation in homes. People often focus on these costs in arguing for "negative-cost opportunities" (actions that can be taken that save money). For instance, additional insulation in homes is often cost-

[23] Jaffe et al. 1995 provide a more detailed taxonomy that includes government administration costs, transaction costs, and other elements.

effective over the lifetime of the home. Yet, due to myopia, imperfect capital markets, and imperfect information on the part of home buyers, such negative-cost actions are often not taken.

The next level of costs includes these direct outlays but also includes more subtle costs that result in a reduction in producer and consumer surplus. Examples for a producer would be accelerated depreciation of fixed capital when relative prices change (older fuel-inefficient cars drop in value when the price of energy increases) and adjustment costs associated with changing production processes. For consumers, having to forego activities that have become more costly results in lost utility, lost surplus. The sense in which these factors are considered partial equilibrium effects is that the consequences of an elevation in the price of GHG emissions are not being traced through the entire economy. The price of gasoline goes up and consumers and producers of gasoline adjust, keeping other prices constant.

The third level of costs encompasses all economic costs of GHG control, taking into account the many indirect and feedback effects that take place within a modern economy. For instance, when the price of carbon increases, the price of oil (net of tax) would be expected to decrease. This scenario would depress the oil industry and thus have consequences for firms providing inputs to the oil industry, to local industry dependent on worker income from the oil industry, and to local universities dependent on oil revenues for finance. These latter sectoral effects are what would be considered secondary effects, not normally picked up in a partial equilibrium analysis. These effects may be minor, as would be expected for small changes in a part of the economy. It is also important to separate short-term adjustment costs (including temporary unemployment) from long-term equilibrium adjustments.

Somewhat ambiguous are the costs generated by preexisting distortions such as labor taxes in the economy. When carbon taxes or other carbon policies exacerbate the inefficiencies of labor taxes, should those additional costs be laid at the feet of the carbon tax? If there were no labor tax, there would be no extra inefficiency from the carbon tax. As Coase might suggest, either the carbon tax or the labor tax could be blamed for the extra inefficiency. But which to blame is not the point; the fact is that there will be an additional cost to society that results from an increase in the carbon tax (see Goulder 1995). Moreover, these costs can be ameliorated in part through judicious recycling of tax revenues, in contrast to revenue-neutral policies (Parry et al. 1999).

Economists note that not all dimensions of human welfare are reflected in the value of market goods and services and the utility that accrues from consuming these goods and services. Certainly there are many aspects of the benefits of GHG control that are outside the market; for example, enhanced ecosystem well-being. Thus it is easy to argue that there may be some costs of GHG control that will not be reflected in the marketplace. For example, long-term unemployment could result from policies that rein in GHG emissions, and the human toll of unemployment includes nonmonetary factors.

2. Bottom-up vs. Top-Down

No review of the costs of GHG control would be complete without some attention to the debate that has been dubbed “bottom-up vs. top-down,” based on the general way in which costs are computed. In computing control costs, the bottom-up moniker derives from the use of detailed models of the cost of GHG control. These detailed models attempt to enumerate many of the abatement options available to specific consumers, producers, or sectors. Attaching costs to each of these options, it is possible to determine least-cost ways to reduce GHGs. For instance, a model could include a housing sector within which the options for reducing the heating needs for a typical house are enumerated (for example, insulation, smart thermostats, roof color). These models can be thought of as engineering-oriented because the choice of technology is purely cost-based without much behavioral content. Because of the assembling of aggregate cost measures from very micro-level data, this approach has been named bottom-up.

The top-down approach derives from observing behavior as relative prices change. We have some experience with how consumers and producers respond when energy prices change, based on three decades or more of a roller coaster of crude oil prices. Top-down estimates of the cost of control are not concerned with exactly what, technologically, a consumer or producer does when the price of energy changes, but rather what the overall result is in terms of energy consumption.

One would think that the top-down and bottom-up approaches to estimating the aggregate cost of GHG control would yield approximately the same marginal cost curve. After all, both approaches involve behavior of the same agents in the economy and seek to measure the same factor, the cost of controlling GHGs. Yet, the top-down estimates of control costs are typically higher than the bottom-up approaches. The reasons for this discrepancy are not altogether clear. One explanation, however, is that the bottom-up modelers are inevitably optimistic. They identify technologically feasible cost-effective approaches for reducing GHGs. Technological feasibility is clearly a necessary condition for undertaking GHG control. However, many other factors besides technological feasibility ultimately enter into the decision as to how to control GHGs, factors that can only increase costs above the least-cost technologically feasible strategy (Jaffe et al, 1999).

A somewhat extreme example illustrates this point. Suppose we examine household use of the family car for local travel around the neighborhood. The question is, if the price of gasoline goes up, how much use can be curtailed? A bottom-up analysis might suggest that use could be curtailed dramatically. The household members could carefully assemble a shopping list and go to the grocery store only once a week or even less frequently. Trips to work could be consolidated with neighbors. Miscellaneous errands could be aggregated into the weekly shopping trip. The opportunities for reducing use seem tremendous. A bottom-up analysis might show that a small increase in the price of gasoline would result in dramatic reduction in gasoline consumption. Or perhaps the analysis would demonstrate the opportunities to reduce gasoline consumption that have no cost at all; the trip consolidation described above is a good idea no matter what the price of gasoline.

A top-down view of this problem would be quite different. The top-down view is that many factors enter into the decision about how to use a vehicle, even for such mundane tasks as trips to the grocery store and running errands. Convenience, imperfect planning, and the value of time all enter into the decision. The best measure of how the consumer will cut back on gasoline consumption is to observe how that consumer cut back the last time the price of gasoline increased.

From this example, we can see that the top-down view may very well result in a larger cost to reduce gasoline consumption by some fixed amount, relative to the bottom-up approach. The bottom-uppers will likely counter that the past is not the correct indicator of the future, and that the top-down approach assumes away extant inefficiencies. They would argue, for example, that if people are educated about how to manage their car use, they can save more energy than they have in the past.

It is easy to see why these two schools of thought can generate dramatically different estimates of the cost of controlling GHGs. It is also easy to see how the bottom-up analyses generate negative-cost estimates of control for modest control levels; society can actually save money by undertaking some control.

3. Costs are Relative

In a well-publicized paper, Costanza et al. (1997) generated measures of the value of the world's environment, including the air we breathe and the world's oceans. One of the criticisms of this analysis was that economic value is relative and incremental, not absolute and total. The value of the air we breathe is defined as the difference in well-being for having air to breathe versus not having air to breathe, which is clearly a large number but a somewhat meaningless one.

Similarly, the costs of GHG control must be relative to some benchmark, particularly if considering the fact that costs are not incurred at one point but continue into the foreseeable future. If we impose a carbon tax and attempt to measure the cost of this tax in 2020, what are the relative costs? Logically, the base is no carbon tax.

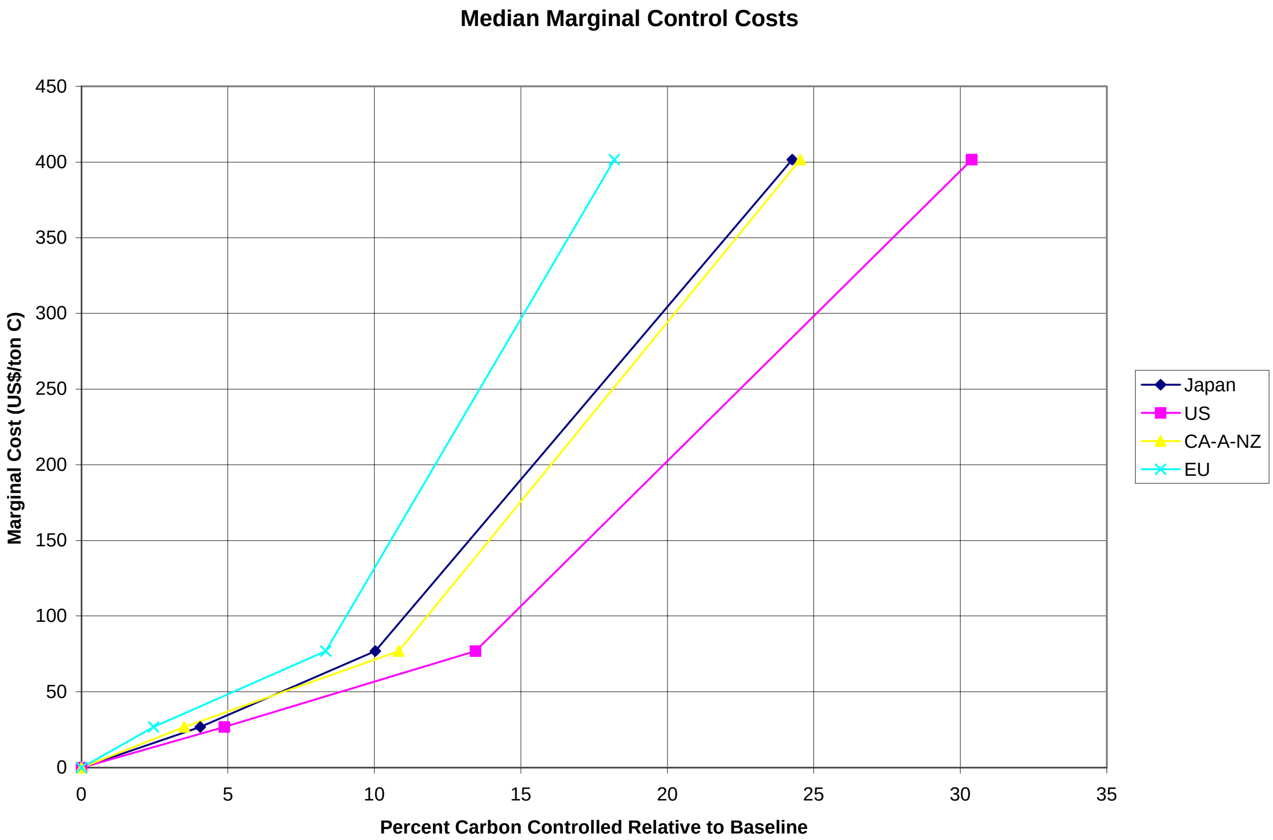
Viewing costs through this lens, it is clear how to deal with preexisting distortions such as the inefficiencies connected to the current tax system. The current second-best economy is part of the baseline. Additional costs induced by a carbon tax, whether direct or due to an exacerbation of inefficiencies from other taxes, are all attributable to the carbon tax policy.

4. Estimates of Control Costs

A number of studies focus on the aggregate cost associated with controlling GHGs or, more specifically, CO_2. Many of these studies have been done for the United States, where the data are more readily available. Hourcade et al. (1996b) provide a very comprehensive, though now slightly outdated, review of estimates of the cost of GHG reduction.

A more up-to-date, though similar, estimate is provided by Weyant and Hill (1999), who report on the results of a comparison of different analyses of emission control costs. This comparison, conducted under the auspices of the Energy Modeling Forum at Stanford University, involved nearly a dozen integrated assessment models adopting the same basic assumptions. Different models similarly calibrated are then compared in a number of dimensions, including the marginal cost of GHG control. Figure 1 shows the central tendency of the estimates of the marginal cost of control for four regions of the world: the United States, the European Union, Japan and Canada/Australia/New Zealand.[24] Although it is not apparent from the figure, there is considerable dispersion around each of these lines, in terms of estimates from the different models. For instance, for the United States, the country probably most studied, the estimates of the marginal cost of control for 25% reduction range from $60 to $300. Obviously, for lower levels of reduction, the dispersion is smaller in absolute terms.

[24] What is shown in the figure is the estimate from the MS-MRT model (Bernstein et al. 1999ab), which is very close to the median estimates (over all models) of the marginal cost of control.



Source: Stanford Energy Modelling Forum data, adapted from Weyant and Hill (1999) with detailed data graciously provided by John Weyant.

Figure 1. Central Tendency (Over Several Different Model Estimates) for Selected Regions of Marginal Cost of Control of Carbon Emissions vs. Percent Reduction in Carbon Emissions
(1990 US$ per ton of carbon vs. percent reduction from year 2010 baseline)

Two factors from the figure are worth noting. One is the considerable difference in the marginal cost of control for different regions of the world. This difference may be because of the endowment of low- versus high-carbon fuels, because of the existing structure of the economy, or because the economy may already be relatively noncarbon-intensive, making further reductions more difficult.

The second feature of this figure is that modest carbon control—less than 10%—can generally be achieved at marginal costs less than $100 per ton and, in some cases, considerably less than $100 per ton of carbon. For comparison, a $100-per-ton carbon tax translates to about

$12 per barrel of crude oil, or $0.25 per gallon ($0.06 per liter) of gasoline.[25] These figures are consistent with typical estimates of the price elasticity of energy demand and the effect such a carbon tax would have on the price of energy.

The costs of carbon sequestration are also relevant to a discussion of the costs of reducing greenhouse gas loading to the atmosphere. Hourcade et al (1996b) report on a number of cost studies of sequestration in forests. There appears to be little consensus among the studies reported, with estimates ranging from $5 to $187 per ton of carbon stored (Hourcade et al, 1996b; p 353). As noted previously, engineered carbon removal from emission streams coupled with sequestration is a speculative but technically feasible long-term possibility, with high costs today (hundreds of dollars per ton of carbon removed and stored) but the prospect of lower costs in the future.

B. Benefits of Greenhouse Gas Control

There are benefits to reining in global GHG concentrations as well as costs. These benefits, however, are harder to quantify let alone monetize. The problem is that the climate affects just about every dimension of human activity on earth. Furthermore, regional physical impacts are highly uncertain – not just in size, but sometimes in sign. To comprehensively characterize what might be the consequences of climate change is daunting to say the least.

1. Scope of Benefits.

Pearce et al. (1996) provide a useful overview of the extent of damages from climate change, which, as was stated earlier, is the flipside of the benefits from avoiding climate change (see also Smith and Tirpak, 1990 and Fankhauser and Tol, 1996). A good deal of work starts from the simplified assumption that climate change involves an increase in the mean temperature and/or the mean sea level. A very much smaller body of work addresses issues of increased variability or nonincremental changes such as changes in major ocean currents.

One type of benefit is avoiding the sectoral consequences of avoiding an increase in mean temperature in sectors such as agriculture, construction, tourism, and manufacturing. Much of the work in quantifying these sectoral effects has focused on agriculture and forestry (e.g., Sohngen and Mendelsohn, 1998, 1999), although other sectors may be affected. For instance, it has been

[25] Assuming a carbon content of .117 tons of carbon per barrel of oil (EIA 1999).

suggested that construction will benefit from warmer weather although increased precipitation, which often accompanies warming, will cause problems for construction.

Another benefit of curtailing change occurs from avoiding the loss caused by sea-level rise. A number of studies have estimated the cost of sea-level rise; the most obvious is loss of land, formerly coastal, inundated after the sea rises (e.g., Yohe et al, 1995, 1996). Others have pointed out, however, that the amount of coastal land stays roughly constant, that a new coastline replaces the old. What is lost is the inframarginal lands as the coastal area is pushed inland. Furthermore, fixed capital (factories, buildings, and infrastructure) and ecosystem values (coastal wetlands) could be lost or disrupted because of the rising ocean.

The energy industry also is expected to be affected by climate change. At the most obvious level, demand for air conditioning will increase and demand for space heating may decrease. Many electricity producers are also concerned about the reliability of their system, particularly in the face of increased variability of weather and an increase in the number of extreme events. Transmission lines are particularly vulnerable.

Water supply infrastructure could also be vulnerable (Frederick and Gleick, 1999). Changes in precipitation will clearly change the appropriateness of the current infrastructure of dams, reservoirs, and water conveyance. Further, sea-level rise may increase the intrusion of salt water into coastal aquifers.

An impact of climate change on human health is also anticipated. Not only could elevated temperatures increase physical stress during hot summers, but disease-carrying insects may migrate. It has been suggested that mosquitoes harboring dengue fever and malaria may expand their territory and thus increase human population exposure.

An additional set of benefits are often called "co-benefits." These are associated with the benefits of reducing levels of pollutants whose emissions are positively correlated with greenhouse gas emissions. Typically, reducing greenhouse gas emissions involves reducing fuel combustion and thus reducing emission of pollutants associated with fuel combustion (Burtraw and Toman, 2001; Ekins, 1996).

Many nonmarket effects of climate change are also important, ranging from ecosystem effects to the amenity value of changed climate.

2. Quantitative Estimates of Benefits

A large number of studies have focused on very narrowly defined sectors and the damage from climate change in those sectors. Pearce et al. (1996) review many of these studies. Far fewer studies have sought to generate an aggregate estimate of the damage from climate change. In fact, most of these studies have focused on the United States, in part because data are more readily available and because the bulk of the narrowly defined studies have been carried out in the United States. Table II presents a summary of five estimates of damage, hypothesized to result from a doubling of CO_2 concentration in the atmosphere (note that the consequent temperature change varies from study to study).

An examination of Table II indicates remarkably little agreement in the details, although the overall impacts have a relatively narrow range from $55 billion to $140 billion. This is a

Table II. Five Published Estimates of U.S. Climate Change Impacts from a Doubling of Carbon Dioxide (billions of 1990 US$).

SECTOR	Nordhaus (1991) 3°C	Cline (1992) 3°C	Fankhauser (1995) 2.5°C	Tol (1995) 2.5°C	Titus (1992) 4°C
Market impacts:					
Agriculture	–1.1	–17.5	–8.4	–10	–1.2
Energy	–1.1	–9.9	–7.9	—	–5.6
Sea level	–12.2	–7	–9	–8.5	–5.7
Timber	—	–3.3	–7	—	–43.6
Water	—	–7	–15.6	—	–11.4
Total market	**–14.4**	**–44.7**	**–41.6**	**–18.5**	**–67.5**
Nonmarket impacts:					
Human life	—	–5.8	–11.4	–37.4	–9.4
Migration	—	–5	–6	–1	—
Extreme events	—	–8	–2	–3	—
Human amenity	—	—	—	–12	—
Recreation	—	–1.7	—	—	—
Species loss	—	–4	–8.4	–5	—
Urban infrastructure	—	–1	—	—	—
Air pollution	—	–3.5	–7.3	—	–27.2
Water quality	—	—	—	—	–32.6
Mobile Air Conditioning	—	—	—	—	–2.5
Total nonmarket	**–41.1**	**–16.4**	**–27.9**	**–55.7**	**–71.7**
TOTAL	**–55.5**	**–61.1**	**–69.5**	**–74.2**	**–139.2**
% of 1990 GDP	–1	–1.1	–1.3	–1.5	–2.5

Source: Mendelsohn and Neumann (1999), adapted from IPCC.

small fraction (under 2%) of the U.S. GDP. In fact, these results have motivated many authors of integrated assessment models, taking their cue from Nordhaus (1994), to view damage from climate change in terms of percent loss in GDP. The U.S. percentage loss figures frequently are extrapolated to the rest of the world. Nordhaus (1994) hypothesizes that a 3°C rise in temperature results in a 1.33% loss in world output. Passing a quadratic damage function through the origin and this single point estimate of loss allows Nordhaus to completely specify damages as a function of the change in the global mean temperature.[26]

IV.Fundamental Economics of the Climate Issue

In this section we lay out the fundamentals of the economic approach to the analysis of climate change. These elements underlie so-called integrated assessment (IA) models of climate change. Our previous discussion emphasizes that to capture the effects of human activities on the climate and the effects of climate change on human well-being, a model must capture the following elements:

- Human activities generate GHGs and alter land use (for example, forest area),which also affects the concentration of GHGs in the atmosphere. These activities, by altering the chemical composition of the atmosphere, are thought to lead to long-term changes in the climate system (temperature level and variability, rainfall patterns, and the like).
- Changes in the climate system are thought to have consequences for human well-being. These changes would occur through a variety of channels (productivity of food and fiber cultivation, impacts on natural ecological systems, threats to coastal areas, human health, and so forth). Thus, a closed loop exists between human impacts on climate and climatic impacts on human society.
- Responses to these feedback effects can reflect a mix of mitigation (reduced emissions, reduced deforestation), and adaptation (before as well as after the fact) which makes human well-beings less vulnerable to climatic change.
- Time is a critical element of the problem. GHGs accumulate in the atmosphere over long periods (decades or even hundreds of years). Capital stock investments that are made in response to climate change threats are also long-lived (decadal periods for electricity generation or road infrastructure), and long-term technical change is

[26] Roughgarden and Schneider 1999 argue that a wider range of damage functions should be considered in assessing the risks of climate change. We return to this point below.

another key influence on the cost of response. Thus, a complete economic analysis of climate change must be dynamic.

- Uncertainty also is a critical element of the problem. The severity of the climate change problem includes uncertainty in the mapping from emissions to temperature and other climatic changes, and in the impacts of climate change on human well-being. The costs of reducing emissions, the evolution of new technologies that will lower that cost, and the opportunities for adaptation are all uncertain as well. Uncertainty further interacts with the dynamic nature of the climate problem in giving rise to issues related to irreversibility, as discussed below. Thus, a complete economic analysis of climate change must also include stochastic elements.

Below we first develop a series of increasingly complex economic models that show how the field has attempted to analyze efficient degrees of climate change and GHG emissions paths. Here, efficient is used in a cost-benefit sense, trading off the present value benefits of avoiding climate change with the costs of doing so. We focus in particular on issues related to dynamics, irreversibility, learning, and insurance. We then step back from the models to discuss more broadly the issues of optimality and efficiency, as economists use these terms, to examine climate policies and discuss some more philosophical issues in this debate.

A. Simple Models of Greenhouse Gas Emissions and Climate Change

We start with the most basic model capable of illustrating some of the key issues surrounding climate change.[27] Imagine a simple economy in which utility, U, is a function of material consumption, c, and the state of the climate as measured simply by average temperature, T. U is increasing in c and decreasing in T. We make the standard regularity assumptions on U: $\lim_{c \to 0} U_c = \infty, \lim_{T \to \infty} U_T = -\infty$, where subscripts denote partial derivatives.[28] Utility can be thought

[27] One of the earliest models is due to Vousden (1973), though Vousden was not concerned with climate change per se.

[28] Neither assumption is strictly speaking necessary; both are used to avoid outcomes in the model in which economic activity ceases in finite time.

of in two ways, as a utilitarian welfare function for the entire society (the representation here) or as the utility of a representative consumer, in which case consumption levels are on a per capita basis (see Kelly and Kolstad 1999).

The consumption good, which can be thought of initially as fossil energy, is extracted costlessly; consumption gives rise to a proportional quantity of GHG emissions, $E = \sigma c$. In this simple representation, we start with a stock of the consumption good, which we deplete over time. There is also a stock of GHGs in the atmosphere, which follows the dynamic equation

$$\dot{M} = -\delta_M M + E \qquad (1)$$

where δ_M is a decay factor.[29] Temperature is related to the stock of GHGs by an increasing function

$$T = \Gamma(M) \qquad (2)$$

This model obviously presents a very stylized picture of both the processes of climatic change and the economy–climate interactions, but it does contain several of the key elements mentioned above. It does not address uncertainties surrounding climate change impacts and mitigation, or tradeoffs between adaptation and mitigation.[30]

The optimal path for human welfare, taking into account material consumption and climatic impacts, typically would be associated with the maximization of the present value of utility subject to Eqns. 1 and 2 and the constraint on the physical availability of the energy/consumption resource. (Again, we return to issues surrounding what constitutes optimal outcomes below.) We denote the social discount rate used in the maximization by ρ . Then, using standard dynamic optimization techniques we can show that the optimal path for consumption, and thus for GHG emissions, is given by the first-order condition

$$U_c = \lambda + \sigma\mu \qquad (3)$$

where $\lambda > 0$ is the shadow price associated with the scarcity of the stock of consumption good and $\mu > 0$ is the shadow cost of GHG emissions. The resource shadow price rises at the rate of

[29] This is a particularly significant over-simplification of some complex physical processes.

[30] Other optimal growth models with stock externalities are presented by Bovenberg and Smulders (1996), Farzin (1996), Kelly and Kolstad (2001) and Kolstad (1996). In the 1970's there were a number of theoretical optimal growth models developed for dealing with stock pollutants (e.g., see Keeler et al, 1971; Plourde, 1976).

discount (consistent with Hotelling's Rule), while the shadow cost of emissions follows the dynamic equation

$$\dot{\mu} = (\rho + \delta_M)\mu + \Gamma' \cdot (-U_T) \tag{4}$$

In this simple model, the only response option for the optimization of the consumption and GHG emissions paths is to delay consumption, thereby slowing climate change and shifting climate change damages into the future when the present value is lower. Equations 3 and 4 show how economic and climatic considerations are tied together in determining the optimal paths. Equation 3 shows how consumption would be shifted through a charge on consumption in addition to the Hotelling scarcity rent. This shadow price reflects the present value of future damage from climate change as a result of current consumption, taking into account the decay of GHGs in the atmosphere over time. It generally would be expected to grow over time as GHGs accumulate but at a decreasing rate as consumption drops because of increasing resource scarcity and the rate of climate change slows.

Imposing the shadow price, through a Pigovian charge on fossil energy consumption, for example, reduces current consumption and thus slows the rate of climate change relative to the no-regulation case. Note, however, that in this model cumulative GHG emissions are not affected by policy because the resource stock is eventually exhausted in any event. The timing of emissions is changed, with greater emissions—and more accelerated climate change—occurring in the future. This simple example prompts some interesting intertemporal distribution questions, which we address below.

This very simple model can be extended in numerous ways. For example, we could introduce a noncarbon "backstop technology" for consumption (switching from coal to solar, for example), which has a higher cost of use than fossil energy but eventually becomes economical as fossil fuels become scarcer and costlier to produce. In this situation, a policy restricting consumption based on use of fossil energy (like a Pigovian carbon tax) will also hasten the transition to the backstop and reduce cumulative GHG emissions as well as shift them into the future. This example is a special case of a more general model of multiple energy forms with different carbon contents (that is coal and natural gas).

A major extension of the analysis toward greater realism is to consider substitution between energy and capital and improved energy efficiency per unit of output, as well as substitution among types of energy and reduced energy use per se. To illustrate this scenario, we can let *d* represent climate damages that are positively related to temperature and economic activity, which is denoted by *Y*. For a given elevation in temperature, damages may well depend on the level of economic activity (more activity, more damages). Economic activity (holding population and labor force fixed for simplicity) depends on services derived from invested capital, *K*, as well as energy inputs and the state of the climate. For the moment, we assume that investment *I* is irreversible, so that $I > 0$, and capital depreciates at the rate δ_K. Assuming for simplicity a constant emissions intensity per unit of energy, we can use *E* to denote exhaustible fossil energy as well as emissions (the model is easily extended to incorporate a backstop nonfossil energy resource). We can then write, in addition to Eqns. 1 and 2,

$$U = U(c, d) \tag{5}$$

$$d = g(T, Y) \tag{6}$$

$$Y = f(K, E, T) \tag{7}$$

$$\dot{K} = -\delta_K K + I \tag{8}$$

Note that this framework allows for adverse climate change impacts through reduced productivity ($f_T < 0$) as well as through direct impacts on utility.

The pathways of climate change impacts and the possible responses are more complex with the introduction of capital–energy substitution. By rearranging the above relationships we can express the economic problem as one of optimal capital investment and GHG emissions. We can write the first-order conditions for the problem as follows:

$$U_c = \eta \tag{10}$$

$$(U_c + U_d g_Y) f_E = \lambda + \mu \tag{11}$$

$$\dot{\lambda}/\lambda = \rho \tag{12}$$

$$\dot{\mu} = (\rho + \delta_M)\mu + \Gamma'[(U_c + U_d g_Y) f_T + U_d g_T] \tag{13}$$

$$\dot{\eta} = (\rho + \delta_K)\eta - f_K (U_c + U_d g_Y) \tag{14}$$

Here, as before, λ denotes the scarcity value of the stock of energy and μ is the shadow price of GHG emissions; in addition, η is the shadow value of capital investment. The term $U_c + U_d g_Y$, which we assume is positive, can be thought of as the marginal utility of output:

Increased consumption raises utility directly but indirectly reduces utility through magnified climate damage. Below we discuss how the relationship between utility and climate change can be viewed in an even more complex manner.

Equation 11 represents a modified Hotelling Rule, which takes into account the ways that increased GHG emissions give rise to welfare-reducing damages over time. It is easily seen from this equation that the marginal product of energy use in the steady state (with $\dot{\mu} = 0$) is higher than in the absence of climate change considerations. This finding suggests (but does not prove) that, in the long-term, emissions are lowered by an optimal climate change policy.

One way this reduction occurs is through substitution of capital for energy. Equation 10 expresses the standard Ramsey Rule for optimal consumption, which is to equate its marginal utility with the shadow value of capital. Equation 14, however, shows that the shadow price of capital is affected by climate change; greater investment increases economic activity, but this approach also increases the scale of damages. If we substitute Eqn. 10 into Eqn. 14 and set $\dot{\eta} = 0$ to look at the steady state, we find that

$$(\rho + \delta_K - f_K) = f_K U_d g_Y < 0 \tag{15}$$

which implies that the steady-state marginal product of capital is smaller than would be optimal in the absence of climate change concerns. This finding suggests (but again does not prove) that capital investment is larger when energy use is limited to take climate change prospects into account.

One last extension worthy of mention is the incorporation of adaptation as well as mitigation activities. Basically, this adaptation involves accumulating knowledge and physical capital stocks such that for any given GHG stock and temperature level, the level of economic productivity and the direct damages of climate change on household well-being are smaller than without the investment. Examples include building flood protection walls and developing drought-resistant seeds or new disease-immunization methods. In contrast to what is developed above, adaptation also could be assumed to occur naturally as a byproduct of economic growth, so that $g_Y < 0$. The argument here is that wealthier societies are less dependent on the natural systems that figure prominently in sustaining welfare in poorer societies. However, at least part of this difference is already reflected in differences in capital stock and factor productivity.

Although the models sketched above are relatively simple, the structure of economy-climate interactions therein is at the core of most integrated assessment models, which are large-scale applied numerical models of climate and the economy (Weyant et al. 1996). The difference is that integrated assessment models have a great deal more detail in particular components of the climate–economy system. Atmospheric processes, the production of goods and services, and the options for controlling greenhouse gases may be represented at a greater level of detail. However, the fundamental structure, at least for integrated assessment models with an economic orientation, is as depicted in our simple model.

B. Uncertainty, Irreversibility, Learning, and Insurance

Integrated assessment models that explicitly incorporate uncertainty are still the exception rather than the rule,[31] but uncertainties regarding both the risk of climate change and the cost of mitigation are drawing increased attention. These uncertainties assume particular interest when the effects of climate change and investments to mitigate those effects are, at least to some degree, irreversible. These uncertainties also give rise to a need to understand learning and its consequences, because the information decisionmakers possess about climate change risks and response costs is hardly static. Finally, uncertainty creates a demand for insurance[32] against the risks of climate change. Our discussion in this subsection focuses on laying out the conceptual issues; below we discuss the findings of particular models.

Uncertainty and irreversibility are discussed in Kolstad (1996a,b) and Narain and Fisher (2000); the former paper also addresses learning (see also Manne and Richels 1992). Irreversibility means that certain actions may be difficult to reverse because doing so is costly or even impossible. More precisely, an asymmetry exists between the benefits of acting and the costs of undoing that action. If one expects to acquire information in the future, information that might be crucial in determining the advisability of taking an irreversible action, then it is optimal to err on the side of not taking irreversible actions, assuming all other things are equal.

The general problem of irreversibility is that, in the face of uncertainty and long-lived impacts, a quasi-option value is associated with the opportunity to delay these impacts until more information is available. This value is based on the expected value of the information that will be received, conditional on deferring the irreversible action (Fisher, 2000; Hanemann, 1989). In

[31] For example, of the 21 integrated assessment models reviewed in Kelly and Kolstad (1999b), only 6 incorporated decision-making under uncertainty.

[32] Tol (1998) more explicitly considers insurance.

other words, taking the irreversible action degrades the value of the information you may receive since there will be less you can do with the information after taking the action. This potential loss is the quasi-option value and must be taken into account when contemplating such actions. In the case of climate change, the impacts involve both the accumulation of GHGs in the atmosphere and the accumulation of capital investments that cannot readily be reversed. The GHG accumulation commits us to the future prospect of a different climate, an outcome that will be especially regrettable if climate change impacts prove severe. Long-lived capital investment implies the commitment of resources to lower GHG technologies, which cannot be easily reallocated if climate change is less severe than expected.

As Narain and Fisher (2000) note, it is important to characterize more precisely what would qualify as irreversibilities in this context. With respect to GHG mitigation, we can imagine that irreversibility includes difficulty in transforming capital in place and a slow rate of capital depreciation (because capital not easily transformed implies less long-term commitment if capital depreciates rapidly). Irreversibility in the context of GHGs can be quite different. In particular, limits on the availability of carbon sequestration, or other means to remove GHGs from the atmosphere, might imply an irreversibility in GHG emissions (Kolstad 1996a). GHGs residing in the atmosphere can be reduced only by slowing new emissions, waiting for existing concentrations to decay, or accelerating sequestration. In any case, it is not costless to rapidly undo the act of emitting GHGs into the atmosphere.

The fact that GHGs in the atmosphere decay with time weakens the irreversibility of GHG emissions, although the weakening is only modest because of the long time required to completely reverse specific emissions. A stronger form of climate change irreversibility arises if the atmosphere never recovers, or—equally relevant for economic analysis—the impacts of climate change do not reverse over time, even if the atmospheric concentration of GHGs drops.

As one would expect, investment and climatic irreversibilities pull in opposite directions in defining the optimal path of GHGs; investment irreversibility supports the argument for delaying some capital expenditures, whereas climatic irreversibility supports the argument for more aggressive near-term abatement. In an analysis of this issue, Kolstad (1996a) argues that the investment irreversibility is stronger than the emissions irreversibility and thus suggests a positive quasi-option value from emission control. This perspective implies the desirability of slightly less control relative to the case where learning is ignored. However, no consensus on this issue exists (see also Pindyck, 2000). Ulph and Ulph (1997), for instance, argue that irreversibilities can lead to over- or under-control, depending on very specific characteristics of utility and production functions. Narain and Fisher (2000) obtain a similar result with their characterization of irreversibilities, including the possibility of modifying existing capital (at some cost), that climatic irreversibility may be of more concern.

C. What Integrated Assessment Models Say

Empirical integrated assessment models use the basic conceptual structure described above with elaborations to better reflect the detail of both energy–economy relationships (which influence mitigation costs) and GHG–climate relationships. A number of these frameworks are variants of the relatively aggregated optimal growth model with GHG accumulation and damage developed by Nordhaus (1993, 1994). Other models provide greater degrees of disaggregation regionally, within the energy sector, or both (see for example Weyant et al. 1996, Kolstad 1998, Weyant and Hill (1999), Yang (1999).

Nordhaus (1994) determines the level of emissions that maximizes net benefits of GHG control. He also compares these results to other policies, such as stabilizing emissions at 1990 levels or stabilizing the climate by limiting temperature increases to 1.5^{o}C over preindustrial temperature levels. He finds that optimal control of GHGs results in reduction of emissions of 9%–13% over levels that would otherwise be expected over the coming century. This estimate could be supported by carbon taxes in the $5–$20 range. In contrast, stabilizing emissions at 1990 levels involves control levels gradually ratcheting up to 60% by 2100 (that is, emissions would be reduced by 60% relative to what otherwise would be expected). Stabilizing temperature involves a phasing-out of carbon emissions by the middle of this century. As for the cost, Nordhaus (1994) estimates that an optimal level of emission control generates net benefits, discounted over the coming century, of US$271 billion We are slightly better off as a result of this emission control. To put this quantity in perspective, it is 0.04% of the net discounted value of global consumption over the century: a gain, but not a big gain. In Nordhaus' analysis, stricter stabilization policies generate significant net economic losses.

The apparent desirability of letting emissions rise well into the next century, if not beyond, is a striking finding and is typical of many IA models (Manne 1996). The models indicate that policies pushing for substantial near-term control, like the Kyoto Protocol, involve too much cost, too soon, relative to the benefits. Several reasons support this finding. Damages rise with the concentration of GHGs in the atmosphere, and, according to the estimates in most IA models, the costs of sharply reducing GHGs today are too high relative to the benefits. Only after the GHG concentration has grown considerably does it make sense, on expected present value grounds, to taper off emissions. In addition, the marginal costs of controlling GHGs are relatively insensitive to the stock of GHGs and the level of control. Thus there is no cost penalty for deferring emissions control.

In fact, IA calculations often presume that the unit cost of GHG control in the future may be lower than in the present, even if a higher overall level of control is needed in the future. This is a consequence of a presumed continuation in trends toward greater energy efficiency in developed and developing countries,[33] as well as some increased scarcity of fossil fuels and falling costs of backstop energy resources. Last, but not least, the finding of IA models in favor of delay in GHG control reflects the fact that with discounting, one seeks to backload both abatement costs and climate change damages.

The models referred to above do indicate, as expected, that higher costs of climate change imply the desirability of more GHG mitigation. However, the level of mitigation remains less than that emphasized in current policy debates, even if the level of marginal damage cost is much higher than is conventionally assumed in IA models (see also Peck and Teisberg 1993).

To explore these issues further, Pizer (1999) uses a model similar to that used by Nordhaus (1993) to examine how taking into account a variety of potentially correlated uncertainties relate to the climate, the economy, and individual preferences, including the rate of time preference. He examines how these uncertainties affect the global emissions path that minimizes the expected present value of damage plus control costs. He finds that with these uncertainties, the optimal time path is substantially—about 30% more—stringent in restricting emissions over the long term compared with the path that results from using best guesses about the uncertain parameters. This finding reflects an inherent nonlinearity of the social cost function; deviations in the parameters that raise social costs are proportionally more important than deviations that lower social costs. However, the results still echo those of other integrated assessment models in that the social cost-minimizing emissions path is significantly less restrictive than the path implied by the Kyoto Protocol targets.

A particularly intriguing feature of the analysis is that about half the increased stringency is attributable to just one parameter, the rate of time discount in the utility function. This finding reinforces the common intuition that the choice of discount rate has a strong influence on the optimal climate policy. Pizer further notes that because low discount rates are correlated with a

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[33] It has been surprisingly difficult to endogenize innovation and technical change within an IA model. See Nordhaus (1997) and Goulder and Schneider (1999).

slowdown of economic growth, his results run counter to the conventional wisdom that lower economic growth implies less concern about climate change, because emissions growth is slower.[34]

Pizer's analysis abstracts from the risk of a catastrophe due to climate change. This analysis is the central focus of a paper by Gjerde et al. (1999), who use their own growth-theoretic integrated assessment model of global economic activity, GHG emissions, and climate responses. These authors show that taking into account a risk of catastrophe, which is correlated with the future buildup of CO_2 in the atmosphere, provides a rationale for current GHG control, even if the risk is small and there are no other hazards (ongoing "continuous damages") posed by climate change. At the same time, however, these authors find that including a catastrophe risk on top of a smooth damage function does not provide that much additional rationale for GHG reduction, unless the risk and severity of the catastrophe are both quite high. In part, this finding may reflect the fact that their model finds social-cost-minimizing GHG control to be more stringent than in many other assessments, a result the authors attribute to greater optimism about GHG control costs in the longer term.

Gjerde et al. (1999) examine the sensitivity of their results to the probability of catastrophe and to the discount rate. Like Pizer, they find that the optimal GHG path is extremely sensitive to the choice of discount rate: Optimal emissions continue to rise for 50 years (though more slowly than in the absence of climate policy) with a 3% discount rate, whereas optimal emissions decline fairly precipitously with a 1% discount rate. It follows that with an endogenous catastrophe risk, the probability of catastrophe over the long term is much higher with a higher discount rate. As one would expect, a higher probability of catastrophe also implies a more stringent control policy. But Gjerde et al. also show that even after taking catastrophe risk into account, it is difficult to rationalize in their model the original goal of the Rio Earth Summit, namely holding emissions below 1990 levels, unless the catastrophe risk is quite high or the social discount rate is lower than the 3% often used in integrated assessment models. Finally, the authors' model confirms another point made in previous studies (for example, Peck and Teisberg 1993), that the value of improved information about climate risks may be quite substantial (see

[34] The choice of discount rate is highly controversial. Weitzman (1998, 2001) has argued that it should slowly decline over time (see also Newell and Pizer 2000). Cline (1992) argues that it should be lower than assumed by Nordhaus (1994) and others. See the proceedings of the two conferences on this subject: Portney and Weyant (1999) and Lind (1984).

also, Nordhaus and Popp, 1997). Roughgarden and Schneider (1999) reformulate DICE to include greater uncertainty. They show that this calls for much more aggressive greenhouse gas control.

Uncertainty need not involve learning. The level of uncertainty can remain fixed over time. In such a case, there obviously is no gain from deferring action in order to reduce uncertainty. The information available to make a decision will be the same tomorrow as today. But when new information is expected, information that may change choices, then the question becomes more complex. As mentioned earlier, irreversibilities may imply that some abatement actions will degrade the value of future information, suggesting moderation in abatement efforts. However, as Epstein (1980) and others (for example, Freixas and Laffont 1984, Zhao and Zilberman 1999, Kolstad 1996b) have shown the direction of the bias is not always towards moderation. The most that can be taken from the theoretical literature is that the precise implications of learning can be understood only with empirical analysis.

Several authors have attempted to determine the consequences of learning for optimal GHG control. As was mentioned earlier, Kolstad (1993, 1994, 1996a,b) and Kelly and Kolstad (1999) examine the optimal level of current emission control with and without learning. Implicit in these analyses is a simple Nordhaus-type optimal growth model with a single capital good. Investment in emission control has elements of irreversibility in that once investment occurs, it becomes a sunk cost. Similarly, GHG emissions can only be "un-emitted" by waiting the decades or centuries necessary for the stock to decay naturally. The no-uncertainty, no-learning result is that current (1995) GHG emissions should optimally be reduced by about 8% relative to un-controlled levels. Introducing learning and uncertainty reduces this figure 5%–7%, depending on the level of learning. Thus the control capital irreversibility appears to dominate the irreversibility of GHG emissions.

This concept can be understood by using the terminology of Ulph and Ulph (1997): Only "effective" irreversibilities yield any bias in optimal actions. An effective irreversibility is one that is likely to bind. The irreversibility associated with GHG emissions is that one might like to reduce the stock of GHGs in the future. However, nearly all states of the world in the models simply involve reducing emission levels to slow the growth of the GHG stock. Desiring to actually reduce the stock is unlikely. Thus the GHG stock irreversibility has little effect on the optimal current period action. Narain and Fisher (2000) find a stronger GHG stock effect by including an endogenous probability of an environmental catastrophe.

D. The Optimal Timing of Emissions Control

The focus throughout the discussion above has been on balancing the present value of benefits and costs in designing climate policy. This line of analysis has had relatively little impact on policy debates so far; we suspect this reaction is due partly to doubts about the completeness of economic damage estimates and partly to philosophical disagreements with the approach of associating optimal climate trajectories with the present value of net benefits. However, another line of research concerned with the optimal timing for achieving a long-term GHG concentration target has had a somewhat stronger impact on the policy debate.

Because climate change is a long-term issue, policy discussion often has focused on different targets for the long-term GHG concentration in the atmosphere. The concentration prior to the start of the Industrial Revolution has been estimated to be around 280 ppmv[35] of carbon, and that concentration had risen by the late 1990s to more than 360 ppmv. A good deal of the noneconomic debate over climate control has been couched in terms of stabilizing concentrations at some level between 450 (tough to achieve) and 750 (much easier to achieve). In earlier stages of the climate policy debate, most policy scenarios, such as those put forward by the IPCC, simply presumed an immediate departure from the business-as-usual (BAU) path. However, Wigley, Richels, and Edmonds (1996, hereafter WRE) show that other paths lead to the same long-term GHG concentrations. They also show that the paths with less short-term reduction balanced by greater GHG reduction in the future could achieve the same long-term environmental objectives at a much lower present value cost (on the order of 50% less or more in some cases). Since WRE's paper, numerous analyses have expanded on the theme (see, for example, Manne and Richels 1997).

The reasons for the lower cost in many ways parallel the reasoning for optimal GHG paths described above. Part of the reason for the lower cost is the advantage of deferring costs to the future, when their present value is lower. Leaving aside the time value of money, only a modest cost disadvantage is associated with doing more control later rather than spreading control costs out over time starting now. But beyond pure timing, several other advantages of delay figure prominently in WRE's analysis. Delay allows a more gradual evolution of the capital stock, with less premature obsolescence and lower adjustment costs. It also allows greater opportunities for deployment of more energy-efficient capital, assuming continuation of trends

[35] ppmv = parts per million by volume.

toward greater energy efficiency. Finally, earlier emissions have more time to decay and thus contribute less toward elevating the long-term GHG concentration in the atmosphere.

Critics of the WRE finding (see, for example, Grubb et al. 1995, Ha-Duong et al. 1997) have raised both substantive and political economy concerns. Substantively, the critics have questioned the size of the near-term cost of GHG reductions, an issue discussed in the previous section. Critics also have noted that delay increases the risk that rapid and costly GHG reduction would be needed in the future if climate change is found to be a more serious threat. This argument is true in principle but, as already noted, it has force only if risks are found to be catastrophic and imminent. It is a costly, risk-averse strategy to hedge against this possibility while foregoing significant cost savings in other states of the world.

A more engaging criticism is that limiting near-term GHG reductions provides excessively weak signals for inducing the very technology innovation presumed by WRE and others as a rationale for delay, while allowing greater “lock-in” of GHG-intensive technology that is costlier to alter later. This criticism is no doubt true to a degree; the question is the extent to which this condition is a problem and what the are options for overcoming it. If a more gradual emissions control path generates significant cost savings, some of these savings can be invested in promoting R&D. As for the degree to which innovation is retarded, Goulder and Mathai (2000) find that the presence of induced technological change generally lowers the time profile of the carbon taxes required to obtain alternative concentration targets. The impact of the induced technological change on the least-cost abatement path varies. When knowledge is gained through R&D investments, some abatement is shifted from the present to the future, thereby supporting the notion of backloading. When knowledge is gained through learning by doing, however, the impact on the timing of abatement is ambiguous. Another aspect of that perspective, according to Kelly et al. (2000), is that aggressive control of GHG emissions makes learning about the climate more difficult because the greenhouse “signal” is diluted. Their result is quite qualified, however, and stops short of suggesting that emissions control should be moderated to increase learning. Clearly, further research is needed on these issues.

E. Philosophical Justifications for Climate Policy

Ultimately the strength of the economic approach to analysis of climate change risk depends on the extent to which its prescriptions accord with the way people actually perceive the risks, costs, and policy options. Three main types of criticism have been leveled at the economic approach. One is the general criticism that individuals do not consider benefits and costs or evaluate risks as presumed in the economic model. Although there is reason to wonder about the capabilities of the standard expected utility model to describe how people evaluate low-probability, high-severity events as might occur as a result of climate change (see, for example, Camerer and Kunreuther 1989, Viscusi 1992), the economic approach is both logically consistent and relevant to the problem of climate change. Moreover, other paradigms are equally plagued in practice with problems related to uncertainty, and there is no consensus on an approach that can do better. So we put aside this general critique and focus more on specific concerns related to the nature of the climate change threat.

One such critique is that the economic model presumes too much substitutability between the different forms of “natural capital” that could be degraded by climate change and compensatory investments in knowledge, technology, and built capital. As a result, the argument goes, economists understate the cost of climatic change and overstate the potential for adaptation. This criticism is of course difficult to either prove or refute a priori. There is growing evidence of a capacity to adapt to climate change in areas where humans have a significant capacity to manage the ecological system. As discussed previously, agriculture and forestry are two examples; another example might be the development of means to avoid or treat tropical diseases whose incidence would be raised by climate change.

Adaptation capacity is linked to societal wealth and infrastructure, which means that limited adaptation is at least in part a problem of poverty, not an inherent problem. We can be less confident about adaptation capacity when the impact involves parts of the ecological system where humans have less control, such as with biodiversity. This aspect represents a challenge for future research. (It is also worth noting that the issue of limits on substitution is a double-edged sword. Positing limited substitution opportunities also means a high cost of reducing fossil fuel emissions for the current generation, reducing society’s willingness to invest in limiting future climate change.)

The other critique we address relates to intergenerational fairness. Critics of IA models note that the advantages of slow response to rising GHG concentrations reflects, at least in part, the effect of discounting and that, given the long time horizons involved, such delay reflects intergenerational wealth transfers, not just rational allocation of expenditures over one generation (Howarth 1996, 1998). The argument implies that to the extent deferral of policy response reduces the well-being of future generations, the application of the present value criterion gives rise to ethical concerns. Emanating from this point is a complex maze of arguments concerning how benefits and costs should be discounted over time in assessing climate change risks and policies, and how responsibilities to future generations should be defined.

Advocates of the conventional economic approach offer several defenses of present-value cost–benefit analysis (see, for example, Weitzman 1999). If economic progress continues, future generations will be better off than the current generation. If economic progress were impeded by climate change, a variety of ways would exist to make compensating investments in addition to GHG mitigation at present. We do no favors to our descendants, this reasoning suggests, if we invest in GHG mitigation with a lower social return (as we reckon it) than other options. This argument explicitly assumes a significant substitutability between natural capital adversely affected by climate change and other assets. Finally, the evidence concerning intergenerational altruism is itself ambiguous, or else aid to disadvantaged persons today would be greater (Schelling 1997).

Unfortunately, our empirical understanding of all these matters is limited. It does seem clear that to evaluate the economic cost of GHG measures, discount rates that reflect the appropriate intertemporal opportunity cost—whatever that may be—should be used. As for what level of investment is appropriate given the uncertain future risks of climate change and our uncertain degree of intergenerational altruism, only time and a great deal more political debate will tell.

Critics have proposed alternative criteria to replace benefit–cost analysis. However, the alternative approaches are actually particular ways to weigh the benefits and costs of policies, given uncertainties, risks of irreversibilities, risk aversion, and distributional concerns. For example, the precautionary principle seeks to avoid undue harm to the climate system, and cost considerations are absent or secondary. This approach is equivalent to assuming that a sharp jump exists in the damages beyond the proposed threshold. This situation may be the case, but as yet no clear evidence exists for assuming that damages have this property (let alone for locating the level of climate change at which such a jump would occur).

"Knee of the cost curve" analysis seeks a rule for limiting emission reductions at a point where marginal costs increase rapidly. Benefit estimation is set aside in this approach because of uncertainty. The approach implicitly assumes that marginal damages from climate change do not increase much as climate change proceeds, and that costs could escalate rapidly from a poor choice of emissions target. Whereas costs will indeed increase with the stringency of control, if the benefits of action are not considered, a sound decision cannot be ensured.

Benefits and costs are unavoidable; how differently people choose to weigh the impacts separates one approach from another. Thus, we maintain throughout this discussion that the assessment and weighing of costs and benefits is an inherent part of any policy decision, something that cannot and should not be avoided by appealing to any oversimplified decision criteria.

V.Designing Climate Policy Instruments

Economic analysis of climate policy design has focused mainly on the application of incentive-based instruments for GHG abatement, such as charges for carbon emissions, tradable permit or credit systems, or hybrid policies (discussed below).[36] As standard theory indicates, such policies create tangible financial reasons and provide flexible means to reduce carbon emissions at lower cost. They also provide incentives for innovations that reduce costs of future GHG abatement. Specific responses to incentive-based policies include:

- switching to less carbon-intensive fuels (for example, natural gas for coal)
- increasing energy efficiency per unit of output by using less energy-intensive technologies
- adopting technologies to reduce the emissions of other GHGs (assuming these other gases are covered in the tax program)
- reducing the production of what are now higher-cost carbon-intensive goods
- increasing the sequestration of carbon through reforestation and other measures
- developing and refining new technologies for avoiding GHG emissions (for example, renewable energy resources).

Because the basic theory of these policies is familiar, we focus here on specific issues that arise in applying these tools to GHG abatement, both domestically and internationally. These include cost-effectiveness, performance in the face of uncertainty, incentives for innovation and distributional concerns.[37] Toward the end of this section we also consider the

[36] Energy policies and GHG policies are related, but they are not the same thing. For example, a uniform tax on energy would be inefficient from a GHG control perspective because it would excessively penalize lower-carbon energy forms. Moreover, R&D policies directed at overcoming market failures in the development of new technologies may or may not favor lower-carbon energy forms. Reforms of energy subsidies will reduce energy use generally but could still favor more or less carbon intensive fuels.

[37] Other factors to consider in evaluating policies include transactions and administrative costs, monitoring and enforcement capacity, distributional and transparency.

need for a technology policy distinct from GHG regulation, as well as policy to promote adaptation.

A. Designing Incentive-Based GHG Abatement Policy: Fundamentals

Taxing carbon is done most easily in an indirect fashion, by taxing fossil fuels.[38] The carbon content of the fuels is easily ascertained, and at present no cost-effective option exists for "end-of-pipe" carbon abatement ("scrubbing"). A fossil fuel tax could be collected in several ways: as a severance tax on domestic fossil fuel output plus an equal tax on imports or as a tax on primary energy inputs levied on refineries, gas transportation systems, and coal shippers, or further downstream. The further upstream (closer to extraction) the tax is levied, the less carbon leaks out through uncovered activities like oil-field processing, and the smaller the number of sources to be regulated. The tax would be relatively straightforward to administer in the United States and most other developed countries, given the existing tax collection apparatus. Tax implementation would be more challenging in those developing countries with ineffectual institutions for levying taxes and monitoring behavior, or where the fiscal system is not transparent and there is the prospect of offsetting hidden subsidies (see da Motta et al, 1999).

Trading carbon is somewhat more complicated than a carbon tax. The most straightforward policy operates upstream by requiring those who produce or import the fossil fuels to have permits (Fischer et al. 1998, Hargrave 1998). A more downstream approach would focus first on larger sources like power plants. Excluding other sources threatens the cost-effectiveness of the program. However, capturing more emissions would require the costly extension of emissions permit trading to small sources, or other policies that cover the sources not in the larger-source trading system (for example, fuel taxes or efficiency standards). This policy could easily lead to differential shadow prices of carbon across sectors, also undermining the cost-effectiveness of the system.

Why then are policies other than a carbon tax or upstream trading seriously being considered? One reason, to which we return below, is that some advocates in the policy process do not have faith in the ability of market signals to produce desired outcomes (at least not on their own). The other reason has to do with distributional and political economy issues. Carbon taxes and upstream carbon permits are fairly transparent signals of regulatory-induced scarcity.

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[38] Some exceptions would be needed for fossil fuels that go into chemical feedstocks or other nonbustive uses (for example, road asphalt).

Other policies may be less transparent in their impacts, including downstream permits that are distributed gratis.

How to distribute permits is another key issue in carbon trading (upstream or downstream). Instead of issuing them gratis (for example, through “grandfathering” to existing emitters), a government could auction permits to the highest bidder. Cramton and Kerr (2001) discuss potential auction designs. The choice forces policymakers to address tradeoffs among goals of economic efficiency, distributional equity, and political feasibility. Efficiency increases with auctioning because the revenues can be used to offset existing distortionary taxes. Parry et al. (1999) estimate that a nonrevenue-raising carbon-trading policy could significantly increase the net social cost of compliance, possibly making the overall emission reduction program a welfare loss rather than a welfare gain. Hoel (1998) shows that revenue-raising policies used to offset other taxes can have positive effects on employment in a less than full employment economy.

However, gratis permit allocation can target the distribution of a valued commodity toward people most adversely affected by the policy (for example, low-income households, coal miners) or those wielding the greatest political influence over the distribution of trading profits and losses. Another possibility is that the allocation can become a political bargaining chip in the policy debate, winning support from emitters who stand to gain under some proposed allocation system, including recipients of permits who do not have a particularly strong claim to compensation on equity grounds. This system, no doubt, can increase the political feasibility of a trading policy. Bovenberg and Goulder (2000) provide some simulation analyses suggesting that efficiency is sacrificed from compensating fossil fuel producing companies and their shareholders for losses stemming from reduced sales under a trading system is not that large. The price tag gets bigger, of course, if one also seeks to compensate fossil fuel intensive industries and the affected workers.

Which GHGs to cover, beyond CO_2, is another issue that trading and taxation policies must address. For instance, the appropriate tax on natural gas entering the pipeline system could account for leakage and the greater relative potency of methane as a greenhouse gas. Levies or permit requirements could also be placed on methane releases from coal mines and landfills and on human-manufactured gases based on their expected recycling or venting to the atmosphere through sources like auto air conditioners. Some gases will be more difficult than others to cover. A prime example is how to capture decentralized sources of agricultural methane that would be costly to measure.

Tax or trading systems could also be extended to carbon sequestration activities such as reforestation programs that could earn tax credits or garner tradable emissions offsets (see the papers in Sedjo et al. 1997). One important challenge here is to define credible measures of the level of carbon sequestered by a forestry project. Part of this difficulty reflects unpredictable natural variability in carbon storage. Moreover, one does not want a system that rewards carbon sequestration that would have occurred anyway as part of forest rotation practices, or a system that encouraged deforestation so that landowners could then claim credit for regrowing trees. Moreover, increased forest preservation in one location could simply stimulate more tree cutting elsewhere; or increased timber supplies as a consequence of expanded forest areas could drive down stumpage prices and increase demand for wood products.

These baseline and "leakage" issues need to be addressed in ascertaining what carbon credits would be awarded to sequestration activities. Note that these issues arise at two geographic scales – the level of specific sequestration projects, and the national level. With a proper accounting system, it is possible to develop tolerably accurate measures of changes in net carbon storage in forests at a national level (Noble and Scoles 2001).[39] At least in principle, then, credits can be given for increases in carbon storage relative to some historical baseline, while purchase of carbon permits could be required for changes in land use that cause release of carbon. At a project level, in contrast, issues of baseline and leakage are harder to sort out, and some rules of thumb likely would be needed.

B. Price Versus Quantity Policies: "Hybrids"

There is a longstanding debate in the environmental economics literature of price versus quantity instruments to address environmental problems (Cropper and Oates, 1992). The widely recognized argument by Weitzman (1974) holds that taxes fix the price and allow the emissions levels to vary, creating uncertainty about the environmental outcome though the firm will know its cost of compliance. In contrast, permits fix the emission target and allow the price to vary, creating compliance cost uncertainty because the price of a permit is not known in advance.

Pizer (1997, 1999), Hoel and Karp (1998), and Newell and Pizer (1998) extend the Weitzman argument to show that a tax is likely to be more efficient than a permit-trading system in the face of uncertainty. Given any particular GHG concentration, the marginal damage

[39] Other measures of biological sequestration, such as from agricultural lands, are much more uncertain.

associated with any particular emissions rate is essentially constant.[40] This finding means little social loss from having abatement vary with the marginal cost under a tax policy, but a potentially large loss from having a fixed abatement requirement in the face of cost uncertainty. The argument would be different in light of a strong reason to limit GHG concentrations below a certain limit because of the risk of catastrophic damages. But too little evidence exists at this time to reach such a conclusion.

It is also possible to use a hybrid policy based on GHG trading, but with a safety valve if costs go too high (Pizer 2001). In practice, this policy would involve the government issuing additional permits if the price went beyond some predetermined level (which could change over time).[41] Pizer (1999) shows that such a policy can essentially equal the efficiency of a carbon tax.

The choice of price versus quantity policy also depends on how these options affect the rate of innovation. Fischer et al. (1998) show that the performance of either policy in encouraging innovation depends on a number of factors. In addition to the slopes of marginal environmental damage and abatement cost, these factors include the degree to which abatement innovations can be imitated (or, conversely, the degree to which an innovator can appropriate innovation rents from other potential users). Their analysis shows that neither price nor quantity policy options necessarily dominate with respect to impacts on innovation.

As noted above, quantity and price policies also may vary in their distributional implications, depending on how they are designed. These differences arise prominently in considering international implementation of GHG policies, as discussed below.

C. Intertemporal Flexibility and GHG Policy Design

Rules for banking and borrowing carbon permits (over time) are another key component of a trading system. Viewed as short-term measures, banking and borrowing lower compliance costs by allowing hedging against risks in emissions patterns (for example, a colder than average

[40] This follows from the fact that an increase in the emissions rate at any point in time will have only an insignificant nugatory effect on GHG concentrations, and thus on damage. As concentrations rise, the argument of Newell and Pizer (1998) would imply an increase in the optimal carbon tax given a rising marginal damage as a function of concentrations.

[41] A policy for U.S. implementation of a safety valve system is sketched in Kopp et al (1999). If permits are internationally traded, rules would be needed to prevent entities in the United States from selling off all their "base" permits to trigger the safety valve. In essence, either countries would need to have harmonized safety valves, or international carbon trading (discussed below) would have to be limited.

winter) and smoothing out fluctuations in abatement costs over time. The Kyoto Protocol provides a very limited amount of such flexibility by allowing Annex I countries to average their emissions over a five-year commitment period (2008–2012).

Bigger questions arise in considering banking and borrowing over longer periods (Leiby and Rubin 2000; Parkinson et al, 1999). Banking will be attractive to permit holders whenever the expected rate of increase in incremental GHG abatement cost is higher than the interest rate (the carrying cost of banked permits). On the one hand, such arbitrage opportunities could be seen as a sign of an intertemporally cost-ineffective time path of abatement targets, a path that does not minimize the present value cost of achieving a long-term GHG concentration target. On the other hand, it is possible that such a path is efficient when taking into account both climate change avoidance benefits and compliance costs. In this case, banking allows for an inefficient acceleration of climate change in the future when banked permits are released.

Borrowing could also cause some short-term acceleration of climate change by delaying emissions reductions, though this issue does not seem that significant in practice. More difficult is the fundamental issue of how to make emissions borrowing compatible with credible long-term policy targets. Borrowing will be attractive to permit holders when short-term policy goals are tight relative to long-term policy goals. In principle, one could circumvent this problem with the design of an intertemporal GHG trading program. In particular, policy could set a long-term GHG concentration target and let private actors hit the target most cost-effectively by adjusting their abatement strategies to minimize costs over time (see, for instance, Kosobud et al. 1994, Peck and Teisberg 1998).[42] Such an approach has numerous advantages in terms of cost reduction. Shifting the time profile of emissions control toward the future, while still achieving long-term stabilization of the atmosphere at some desired GHG concentration, means less premature capital obsolescence and more opportunities to take advantage of technical progress in energy efficiency. The resulting intertemporal cost savings could be very large, on the order of 50% or more (Manne and Richels 1997).

But there is reason to doubt the credibility of such long-term targets and thus the enforceability of an intertemporal GHG trading system with an arbitrary concentration target.

[42] In practice, one would not want GHGs to trade one-for-one over time. The reason is earlier emissions have a longer time to be removed from the atmosphere by natural processes than later emissions, so earlier emissions have less effect on long-term GHG concentrations at any point in time. Thus, earlier emissions should require fewer permits per unit of emissions than later emissions.

The dilemma is a classic example of a commitment problem. Current decisionmakers see economic benefits from delaying emissions control. But they cannot bind their successors to undertake the more stringent control measures needed to achieve the long-term concentration target. The no-commitment equilibrium becomes one in which each successive set of decisionmakers pursues policies that are optimal for them, without presuming that the future will pay back any "carbon debt" they accumulate.

In other words, the equilibrium becomes what is predicted by the integrated assessment models, which, as noted previously, indicate the desirability of far larger emissions (less abatement) over the short-to-medium term than in the Kyoto Protocol. These observations suggest that it may be more straightforward simply to negotiate targets over time that are consistent with the willingness to pay and bear the resulting costs, as opposed to setting more ambitious short-term limits and then inventing policies to circumvent them.

D. International GHG Policy Design

Incentive-based GHG policies can be extended beyond national boundaries. Various forms of emissions trading can be used internationally (Wiener 1999, 2001). It is also possible in principle to envisage internationally coordinated carbon taxes (Hoel 1993). Theory says that such policies can generate more cost-effective outcomes than policies with less "where flexibility" (Manne and Richels, 1999; Nordhaus and Boyer, 2000). Carbon taxes explicitly make the location of abatement endogenous, based on differences in marginal abatement cost. GHG trading operates by allowing low-cost producers of surplus permits or credits to profit from selling permits to high-cost buyers, again achieving an endogenous cost-effective allocation of control effort.

Both approaches can, in principle, generate cost-effective results. The predicted cost savings from trading are very substantial, on the order of 50% or more in many instances (Weyant and Hill 1999). However, these predicted cost savings overstate the realizable savings, because they ignore real-world imperfections in the operation of the mechanisms. There are important practical issues of implementation, distributional implications, and governance surrounding both taxes and trading.

The dilemma with carbon taxes (other than the uncertainty about quantitative abatement outcomes) is their distributional implications.[43] Equalized carbon tax rates will have significantly different cost implications for different economies, depending on their per capita incomes and energy intensity. In particular, one could imagine that developing countries might find onerous the domestic cost burden of a high internationally agreed carbon tax. The domestic cost burden would be associated with the restrictions in energy use and associated investments caused by the tax, not the tax revenues themselves. Faced with these costs burdens, developing countries might demand compensation through some international redistribution of tax revenues. It is difficult to imagine how in practice such a redistribution might be achieved. However, differentiating national carbon tax rates creates a new and troubling source of international inefficiency in resource allocation.

International GHG trading is not easily made compatible with a diversity of domestic GHG policies (Hahn and Stavins 1999). Formal international trading of emissions quotas presumes some kind of domestic allowance programs to be smoothly implemented. In principle, more informal trading of project-level emissions credits (see the discussion of “joint implementation” in Section E below) could be used with heterogeneous domestic policy measures. In practice, however, this approach also poses several difficulties.[44]

Our last issue in this section involves the distributional implications of trading policies in relation to carbon taxes (discussed above). Wiener (1999) examines the impact on regulatory instrument choice of two basic legal parameters that differ between national and global settings: voting rules and implementation structures. In a domestic context a regulator can impose either mechanism by fiat. However, international climate treaties depend on countries’ voluntary assent and on implementation through national governments. Wiener argues that international transfers to developing countries are crucial for expanding participation in GHG control and stabilizing

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[43] It might also be possible for governments with less-than-transparent fiscal systems to hide cheating on their carbon taxes through hidden rebates. Governments also might want to signal they have high costs of GHG control to increase their perceived need for revenue redistribution. In contrast, a government in a position to profit by the sale of GHG credits has an incentive to behave as efficiently as possible in abatement (Wiener 1999).

[44] Hahn and Stavins (1999) further describe the practical difficulties of operating a transaction-specific, credit-based joint implementation program internationally with heterogeneous domestic GHG measures and points out the tradeoff between international cost-effectiveness and domestic policy sovereignty this engenders. For example, JI creates arbitrage opportunities if a country’s domestic carbon tax is higher than the price of JI credits; these credits can be used to offset domestic carbon tax liability. This can be ameliorated only by harmonizing the carbon tax with the international carbon market or eschewing international trading.

the atmosphere, and that such transfers are accomplished more flexibly, effectively, and politically safely by the international allocation of GHG rights and their sale through market channels than through intergovernmental redistribution of carbon tax revenues. Babikar et al (2000) use a computable general equilibrium model to conclude that the burden of Kyoto falls mainly on energy-exporting countries.

Cooper (1998) takes vigorous issue with the plausibility of international agreement on emissions trades. He notes that such an agreement would require a grand bargain for the division of vast wealth, and he views the chances of such a bargain as remote. Instead, he argues that GHG policy coordination should focus on urging countries to pursue individual carbon taxes without redistribution. However, if one is less sanguine than Cooper about the prospects that developing countries would impose substantial carbon taxes on their own, and if one rejects differentiated tax rates as too distorting, one is left with a policy solution that involves a very limited commitment to GHG control. Because the levels of national commitment would be so limited, the difficulties in getting agreement on the distribution of carbon quotas also would be reduced.

E. Emission Trading in the Kyoto Protocol

One of the striking features of the Kyoto Protocol is the explicit incorporation of mechanisms for different forms of emissions trading. Superficially at least, a permit system seems to fit naturally into the Kyoto Framework Convention, which has focused on fixed emissions targets and timetables (McKibbon et al, 1999).

Formal trading of Annex I national emissions quotas (presumably devolved to nongovernmental market participants to reap the advantages of emissions trading) is one option under the Kyoto Protocol. This option is the closest to the textbook version of an allowance-trading program.

Another option for Annex I trading is so-called joint implementation (JI). This approach involves project-level credit generation from emission-reducing actions in other Annex I countries.

The third mechanism is another bilateral project-specific option for credit generation, the Clean Development Mechanism (CDM). Under the CDM, emissions reduction activities in noncapped, non-Annex I nations can generate emission reduction credits for Annex I nations. In principle, the CDM could generate both low-cost emission reductions for developed countries and tangible benefits to the host country through the transfer of modern and low-carbon emission technology.[45]

The practical issues with these mechanisms concern the performance of the institutions, their compatibility with domestic policies, and their distributional impacts. A concern with Annex I trading and JI is how to ensure that emission trading does not subvert national emission limits. This situation would occur if a country were a net seller of permits or credits and not meeting its own Kyoto obligations, thereby "exporting" its own noncompliance.

Because both parties are Annex I countries, either or both could be held responsible under the Kyoto Protocol. Holding selling countries liable focuses responsibility directly on the parties in a position to address the problem and ensures that all credits or permits are more or less equally reliable, thereby reducing the transaction costs of trading. Seller liability measures can be implemented before the fact, by requiring all countries to show they have the domestic regulatory capability to limit emissions, and after the fact, by suspending selling privileges for violators. If seller liability is infeasible politically, holding buyers liable when a selling country is found not to have stayed within its treaty limit is another option. But this situation greatly complicates the operation of the trading system, as the "pedigree" of different credits or permits must be assessed, and individual buyers must undertake expensive insurance (for example, holding extra credits) against risks that lie beyond the control of any abatement projects they may personally undertake.[46]

Among the key immediate questions surrounding both CDM and JI is how to design a credible monitoring and enforcement system that does not impose such high transaction costs that it chokes off projects and credit trades. People will not start a project if the time, effort, and financial outlays to seek, negotiate, consummate, and obtain governmental approvals are too onerous. This case is especially challenging in the context of the CDM, where other investment risks may be high in any event and where the heterogeneity of project types makes it difficult to define a reasonable baseline against which emission controls and credits can be assessed.

This situation in turn draws attention to the dilemmas associated with enforcing environmental integrity in the CDM. Because the non-Annex I host country does not have a

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[45] For further discussion of the CDM see, for example, Goldemberg (1998), Jepma and van der Gaast (1999), Grubb et al. (1999), Bohm and Carlén (1999) and Haites and Yamin (forthcoming).

[46] See Kerr (1998) for further discussion of these liability issues.

national emission cap, there is no analogue of national seller liability with Annex I trading that can be used to help support compliance. Only project-level liability can operate. In this context, it may make sense to hold Annex I investors or credit purchasers liable for project performance, even though this policy introduces the problem of quality-differentiated abatement credits noted earlier. The reason is that Annex I investors or purchasers are subject to whatever compliance measures their governments have instituted; and they may have more at stake in the project economically, thus giving them a stronger incentive to carefully manage project performance risks (Kerr 2001). [**CHECK TAR] A further dilemma for international overseers of these mechanisms is that both investor and host have incentives to exploit project-level informational advantages and the lack of a national emissions ceiling in the host country to misrepresent project performance (Hagem 1996).

F. Nonincentive-Based Policies

As already noted, incentive-based policies work to induce the diffusion of existing lower-carbon technology and the development of new technology. This approach leads to the question of whether additional non-market-based policies are necessary to adequately promote climate-friendly technology advance and investment. Proponents of such policies argue that economic incentives are inadequate to change behavior to a degree sufficient to reduce climate risk. They advocate public education and demonstration programs; institutional reforms, such as changes in building codes and utility regulations; and technology mandates, such as fuel economy standards for automobiles or utilization of renewable energy sources for power generation (see Jaffe et al, forthcoming; Weyant and Olavson, 1999).

No one doubts that such approaches might eventually reduce GHG emissions. At issue is the cost-effectiveness of such programs. Advocates of technology mandates often argue that the subsequent costs are negligible because the realized energy cost savings more than offset the initial investment costs. But this view implies a lack of rational decision-making by energy users in that it does not address several other factors that impinge on technology choices. Most economic analyses recognize that energy use suffers from inefficiencies, and that some low-cost opportunities for improved energy efficiency do exist. However, these analyses lead to skepticism that there are large no-regret gains (for a review of recent ;literature on this subject see Jaffe, Newell, and Stavins 2001). Economic analyses also acknowledge a role for government when consumers have inadequate access to information or if existing regulatory institutions are poorly designed. This role can include subsidies to basic R&D to compensate for an imperfect patent system; reform of energy-sector regulation and reduction of subsidies that encourage uneconomic energy use; and provision of information about new technological opportunities (Jaffe et al. 2001; Schneider and Goulder, 1997).

The economic perspective emphasizes the search for real inefficiencies in markets that impede low-cost choices, as distinct from barriers reflecting unavoidable direct or hidden costs including the capacity of technologies to predictably meet user needs. Some failures in the market are apparent, such as energy subsidies that encourage wasteful use, inefficient regulation of the electricity sector, inadequate private-sector incentives for R&D, and shortages of information for purchasers to use in making informed investments. Other barriers are more controversial.[47]

In developing countries, substantial pricing distortions in energy markets and other barriers that stall the diffusion of cost-effective technology can exist (see Lopez, 2001). These barriers can be compounded by other economy-wide policy and infrastructure problems. Where barriers to technology diffusion exist, there is an opportunity for market reforms that improve economic efficiency and environmental performance.[48] This strategy will likely out-perform regulatory mandates for technology diffusion and adoption.

VI. Economics and International Climate Agreements

The sources of climate change risk—fossil fuel use and land-use changes—are globally distributed. Therefore, responsibility for resolving the problem also must ultimately be widely shared. This fact is vividly illustrated by calculations of future changes in atmospheric GHGs presented by Jacoby et al. (1998). These authors analyze the consequences of having continued and strengthened GHG controls within the Annex I industrialized countries, while allowing rapid emissions growth in the developing world. The projections indicate that even if the current

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[47] For further discussion and competing perspectives on these issues, see Geller and Nadel (1994), Metcalf (1994), Jaffe and Stavins (1994), Levine et al. (1995), Interlaboratory Working Group (1997) and Newell et al. (1999). Another issue that arises in this debate is the prospect of stimulating efficiency-increasing innovation through GHG or energy efficiency policies. Economic incentive policies broadly enhance GHG-reducing innovation, as discussed above, though there may be countervailing effects from displacing investment in other innovative activities (Goulder and Schneider 1999). The same assertion cannot automatically be said of technology or market creation policies, which may favor only one narrow range of technology options.

[48] For further discussion of these issues see Blackman (2001) and Lopez (2001).

developed world drives its net GHG emissions to zero by the end of this century, the impacts on the atmosphere would be small.

But the need for global reduction in GHGs to achieve long-term atmospheric stabilization leaves open the distribution of the costs of achieving such a target. The U.N. Framework Convention posits "common but differentiated responsibilities" for rich and poor countries in responding to the risk of climate change. This is often interpreted as applying to emission control responsibilities per se but is equally applicable to the broader issue of cost distribution. The distinction is important because a globally cost-effective GHG emissions control strategy will entail emissions constraints (relative to business as usual) in all countries, not just in the industrialized world (Jacoby et al. 1998). In principle, at least, nations can seek to pursue such a globally cost-effective solution while dealing with economic distributional issues through different forms of international resource transfer.

The international policy objective is obvious but elusive—to find incentives to motivate nations with strong and diverse self-interests to move voluntarily toward a collective goal of reduced carbon emissions. In this section we address two elements of the challenge to establishing and maintaining effective international agreement. The first topic reflects a general dilemma: The more widespread the responsibility, the greater the challenge to maintain a stable agreement because nations have more incentive to free-ride on the actions of other nations. This challenge is compounded by national differences in income, vulnerability to climate change, and capacities to respond. The other topic is the challenge of expanding participation in global climate agreements by engaging developing nations in ways acceptable to rich and poor countries alike. Many of these issues are explored further in the chapter by Barrett in this volume.

A. The Paradox of International Agreements

The problem of achieving effective and lasting agreements can be summarized as follows: A self-enforcing agreement is easiest to close either when the stakes are small or, at the other extreme, when no other option exists (a clear and present risk).[49] One begins with the observation that because no global police force exists to enforce an international climate agreement, an agreement must be voluntary and self-enforcing; all sovereign parties must not

[49] Refer to Barrett, 1994 and Barrett, this Handbook.

have any incentive to deviate unilaterally from the terms of the agreement. Nations share a common interest in responding to the risk of climate change. However, because climate change is a global public good—no nation can be prevented from enjoying climate protection, regardless of whether or not they participate in a treaty—national governments will have limited incentives to reduce GHGs unilaterally.

International agreement, if it is successfully implemented, overcomes this reluctance. By free-riding, however, some nations can be better off remaining outside an agreement. The greater the global net benefits of cooperating relative to the benefits any one country could receive by acting alone, the stronger the incentive to free-ride. A self-enforcing agreement is most easily maintained when the gains from the agreement are small; that is, when the global net benefits from agreement are not much different than not having any agreement. This situation would exist if only a few parties were responsible for most of the problem, or if the threat is so serious that all countries will want to take strong actions unilaterally. In contrast, a self-enforcing agreement is hardest to achieve in the gray area in between, as is the case with climate change, where aggregate risks may be substantial but individual benefits result disproportionately from the actions of others (for more information see Hoel 1992, Carraro and Siniscalco 1993, 1998, Barrett 1994, Bac 1996). Barrett (1994) finds that an international agreement will work only if the gains from the agreement are modest or if the number of participants is very small (a few countries). Unfortunately, these conditions do not bode well for a climate change agreement, at least one involving a very large number of countries.

If the self-enforcing agreement involves just a few big emitters such as the United States and the European Union, total emissions still are likely to be greater than globally desired because many nations will remain outside the agreement. For their part, many decisionmakers in industrialized countries worry about the consequences to their economies by reducing emissions when developing countries face no limits. This scenario could adversely affect the competitive position of some sectors in the industrialized world, while “leakage” of emissions from controlled to uncontrolled countries would limit the environmental effectiveness of a partial agreement. Estimates of this “carbon leakage” vary from a few percent to more than one-third of the Annex B reductions, depending on model assumptions regarding substitutability of outputs from different countries and other factors (Weyant and Hill 1999).

Developing nations for their part have many pressing immediate needs, like potable water and stable food supply, and less financial and technical capacity than rich countries to mitigate or adapt to climate change. These countries also expect to increase energy use and GHGs, both in the aggregate and per capita, as they attempt to increase living standards. These nations have limited incentives to sign on to an agreement they see as imposing unacceptable costs on them.

Signatories who have ongoing relationships can try to alleviate climate change free-riding by retaliating through other threats like trade sanctions (see, for example, Chen 1997). But the force of this linkage and deterrence is blunted in several respects. A nation's incentive to deviate depends on the short-term temptation from cheating relative to the long-term losses from punishment. Participating nations must see a gain in actually applying punishment, otherwise their threat of retaliation is not credible. Credibility problems arise when, for example, retaliation through trade sanctions damages both the enforcer and the free-rider. Moreover, because many forms of sanctions exist, nations would need to select a mutually agreeable set of approaches, which would most likely be another involved negotiation process (see, for example, Dockner and Long 1993).

If sticks have limited effect, what about carrots? One possibility is to find more efficient policies that lower the cost of participation for all countries. In particular, incentive-based climate policies can help by reducing the cost of action for all countries. This approach underscores the importance of the mechanisms for international emissions trading in the Kyoto Protocol. This point is often lost when critics argue that emissions trading will weaken international agreement through the "export" of cheating by a seller country (Caplan et al, 1999; Carraro and Siniscalco, 1998).

Beyond finding opportunities for lowering costs to all participants, it is also necessary to consider possibilities for resource redistribution through side payments to enhance incentives for agreement. This point is especially important in strengthening incentives for participation by lower-income developing countries, whose long-term involvement is crucial but whose willingness and ability to pay is limited. We turn next to this issue.

B. Designing Climate Agreements to Draw in Developing Nations

Equity is a central element of this issue. However, differences in perceptions about what constitutes equitable distributions of effort or cost complicate any agreement. Different approaches to redistribution also have varying consequences for cost-effectiveness and political acceptability. We consider each of these issues in turn.

There is no generally agreed-upon standard to establish the equity of any particular allocation of GHG control responsibility. Simple rules of thumb, such as allocating responsibility based on equal per capita rights to emit GHG (advantageous to developing countries) or allocations that are positively correlated to past and current emissions (advantageous to developed countries), are unlikely to command broad political support internationally. The same case is true of various dynamic “graduation formulas” that seek to gradually increase the control burden of developing countries as they progress economically, though these dynamic approaches do offer more negotiating flexibility (Cazorla and Toman 2001).

Nordhaus (1997) tackles the question of burden sharing and efficiency by proposing an innovative mechanism for revealing the willingness-to-pay by individual countries to reduce climate change. He views the problem as balancing equity with a country’s gain or loss from climate change. Although his mechanism is not fully fleshed out, it illustrates an approach for seeking broad participation in GHG control with equitable burden-sharing.[50] This approach suggests that distributional agreements must emerge endogenously within the framework of international bargaining, as opposed to arising exogenously from consensus philosophical principles (Schelling, 1995).

Assuming that agreement in principle on the allocation of burden is achieved, a variety of mechanisms might be pursued (Rose et al, 1999). Direct side payments through financial or low-cost technical assistance can increase the incentive to join the agreement. Emissions trading also allows side payments through the international distribution of national emission targets. More reluctant countries can be enticed to join with less stringent targets, which allows for sales of surplus emissions quotas, and other countries would have more stringent targets for achieving the same result with respect to overall emissions.

Such an allocation was provided to Russia and Ukraine in the Kyoto Protocol. It is sometimes termed “headroom”, but it has come to be called “hot air” by critics who fear it would slow international progress by undermining overall environmental progress and giving advanced industrial countries like the United States a cheap way out of cutting their own emissions. But had this cost-reducing option not been part of the Kyoto package, it is unclear whether the United States and other countries would have agreed to the Protocol or achieved its goals in practice.[51]

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[50] For discussions of different allocation formulas and their implications see, for example, Burtraw and Toman (1992), Rose and Stevens (1993), Edmonds et al. (1995), Manne and Richels (1995, 1997), Schelling (1995), Rose et al. (1998), and Yang (1999).

[51] See Wiener (1999) for further discussion.

Nevertheless, international reallocations of wealth in permit trading give rise to broader domestic political debates. Imagine, for instance, the domestic debate if the United States administration decided to transfer many billions of dollars annually to Russia for emission permits,[52] or perhaps China in a subsequent agreement. Critics assert a Catch-22 character to international emissions trading: Without trading, mitigation costs are too high to be politically acceptable; with trading, the international distribution of these costs is still politically unacceptable.

This dilemma has caused some observers to promote individually administered national carbon taxes as the only reasonable option (Cooper 1998). This approach, however, is not panacea for distributional concerns. As already noted, there is a problem of allocating rights and responsibilities implicit in any international GHG control agreement, including taxes. The argument for taxes rests on the willingness of the developing world to implement substantially higher energy taxes than they have today. Although some advantages exist for them (for example, more reliable revenue than from income taxes), it is unclear that the advantages are so compelling in practice. If developing countries are not willing to impose substantially higher energy taxes on their own, then persuading them to participate in a coordinated tax regime will require international income transfers. As Wiener (1999) argues, this system is likely to be more inefficient and more politically problematic than redistribution through market transactions for emissions permits. Without such coordination, however, the tax approach becomes an inefficient partial agreement like the Kyoto Protocol, with all its attendant problems.

To conclude this section we return to the previously mentioned approach of graduation rules for developing country participation in binding agreements. Under this approach, developing countries gradually assume greater responsibility over time, or as their per capita incomes rise. Various proposals include staggered participation in emissions stabilization and reduction targets, with the possibility of eventually converging to equal per capita emissions levels (for illustrative analyses, see Edmonds et al. 1995, Manne and Richels 1997, Rose et al. 1998).

The timing and degree of stringency of control for developing countries are parameters that would be settled in international negotiation against a backdrop of some long-term goal for GHG concentration, which limits the scale of global emissions. Thus the negotiation of evolving

[52] See Victor et al. (1998).

obligations for developing countries implies a symmetric set of obligations for developed countries given the concentration target. The more headroom the developing countries are given, the greater the implied stringency of Annex I control. The negotiation of a graduation mechanism thus implies a burden-sharing rule. The rule may be second-best compared with a more direct wealth transfer,[53] but the indirect nature of the burden sharing may make this approach more politically appealing as a medium-term approach then either a negotiated division of carbon quotas or a tax-based approach.

VI.Conclusions

Climate change poses risks to society. As with other environmental issues—though to a greater degree—complex efficiency and equity issues must be addressed. In this paper we have reviewed the nature of the problem and examined how economics has or can contribute to understanding the problem.

What Have We Learned?

More than a decade of research has sought to better understand the interplay between climate change and the world's economy. There are substantial uncertainties in the benefits and costs of policy intervention. Although this is usually the case for environmental protection, the problem is compounded by the very long time horizons involved with climate change and the uncertain geographic distribution of effects. In addition, there are irreversibilities, both in the climate system and in methods for controlling greenhouse gas emissions. These irreversibilities have modest implications for near term control and more substantial implications for long run emission control policies.

Notwithstanding the uncertainties, assessments of the costs and benefits of greenhouse gas control suggest that limited but gradually increasing control is warranted. The very substantial damages necessary to justify immediate significant action have not been identified, at least to date. Regions likely will differ in their vulnerability, with developing countries generally more at risk and some areas at risk of catastrophic damages (e.g., low-lying island states). Generally, however, adaptation will play a significant role in buffering the impacts of climate change, though the effects of adaptation are themselves uncertain.

[53] If graduation is combined with international emissions trading to utilize the most cost-effective abatement possibilities, the result need not be inferior to other burden-sharing schemes.

There has been considerable research on the costs of controlling greenhouse gas emissions. The notion that there are many zero- or low-cost options for control is not generally borne out in economic research. Emission control may be affordable but it is not cheap. There are very real costs at the margin.

The timing of greenhouse gas emission control can have substantial effects on the costs of control without sacrificing the goal of limiting long-term climate change. A more phased-in approach to emission reduction can substantially reduce costs of achieving a given level of GHG concentration in the atmosphere.

Economic analysis has strongly underscored the point that incentive-based policies are desirable for cost-effective and credible GHG control. Moreover, since the costs of greenhouse gas control and mitigation vary dramatically around the globe, policies that allow flexibility in where as well as how emissions are reduced can dramatically lower the costs of achieving climate objectives.

International participation appears to be necessary to effectively address climate issues. But significant challenges exist to establishing agreements that are substantial in their aims and credible in their implementation, given the differences in economic circumstances and other factors that affect national interests in participation.

Research Implications

Identification and monetization of damages continues to be an area where the current state of knowledge is unsatisfactory. Damage estimates are fundamental to understanding the climate problem yet existing knowledge is incomplete. This will continue to be an important area of research.

It is becoming increasingly clear that the adjustment costs of adapting to a different climate are important. Understanding of the nature of these costs, let along their quantification, is poor. This is a ripe area for further research.

The significant gulf between economically efficient climate policies and policies which result from the political process suggests that more needs to be known about the operational and institutional realities of policy mechanisms. This would include improved understanding of the tension between distribution and efficiency, and the nature of institutional frictions and costs that arise in real-world applications.

There has been considerable work on the effect of uncertainty and information on first-best climate control policies. Much less is known about the effect of uncertainty on the formation of coalitions and reaching agreements on controlling stock externalities. For example, are coalitions and agreements more or less likely to form before uncertainty is resolved? This would appear to be a ripe area for further research.

One of the major arguments for early action in greenhouse gas control is that it may spur innovation, reducing future costs of emission control. However, economics has been unsuccessful in quantifying the effects on innovation of a change in relative prices or regulatory stringency. This is clearly an area of research potential with significant policy implications.

Although the evidence suggests that there are no $20 bills laying on the sidewalk, the question of why apparently feasible energy conservation measures are not being pursued remains important. In particular, empirical work in this area that can bridge the gap between the bottom-up view of the world and the top-down view will continue to be important.

Discounting remains a fundamental philosophical question in climate policy, because of the long periods of time involved in trading off costs and benefits. This is not an issue that will be resolved quickly, though progress has been made over the last decade. Remaining issues include reconciling long-term efficiency and dynamic consistency considerations with less well-defined notions of intergenerational altruism.

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