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THE ECONOMICS OF CLIMATE CHANGE

BY STEPHEN J. DECANIO

REDEFINING PROGRESS

Redefining Progress

One Kearny Street, Fourth Floor

San Francisco, CA 94108

1-800-896-2100

Tel: 415-781-1191

Fax: 415-781-1198

E-mail: info@rprogress.org

Website:www.rprogress.org

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Dr. Stephen J. DeCanio

Senior Research Fellow

Stephen J. DeCanio is Professor of Economics at the University of California, Santa Barbara. He received his Ph.D. in Economics from the Massachusetts Institute of Technology in 1972, and taught at Yale from 1972-1978 before moving to UCSB. He served as Senior Staff Economist at the President's Council of Economic Advisers during 1986-87, and three times has been a member of the Economic Options Panel convened by the United Nations Environment Programme to review economic aspects of the Montreal Protocol on Substances that Deplete the Ozone Layer. He was one of the recipients of the U.S. Environmental Protection Agency's Stratospheric Ozone Protection Award in 1996.

Professor DeCanio's research area is the economics of global environmental protection. He has written extensively on factors affecting the diffusion of energy-efficient technologies, including aspects of corporate organization and behavior that pertain to environmental issues. His papers include "Barriers Within Firms to Energy-Efficient Investments" in *Energy Policy* (1993), "Agency and Control Problems in U.S. Corporations: The Case of Energy-Efficient Investment Projects" in the *Journal of the Economics of Business* (1994), "Why Do Profitable Energy-Saving Investment Projects Languish?" in the *Journal of General Management* (1994), and "Economic Modeling and the False Tradeoff between Environmental Protection and Economic Growth" in *Contemporary Economic Policy* (1997).

Stephen J. DeCanio
Department of Economics
University of California
Santa Barbara, CA 93106-9210
Phone: 805-893-3130
Fax: 805-893-8830
decanio@econ.ucsb.edu

EXECUTIVE SUMMARY

Climate change is emerging as one of the central policy concerns of our time. The problems it raises are difficult ones involving science and economics, decision-making under uncertainty, and the balancing of the interests of the generations now alive and those not yet born. Yet despite these complexities, a great deal of common ground can be found for reasonable policies to address the issue. The recent Economists' Statement on Climate Change, signed by over 2,500 members of the American Economic Association, is an example of the kind of agreement on basic principles that can guide the formation of climate policy.

People are concerned about climate change because of damages that can be foreseen and because of the risks entailed in conducting an irreversible experiment with the planet, an experiment whose outcome is presently unknown. Both economic theory and common sense point to the desirability of taking measures to reduce the risks and avoid the known damages. Climate change could result in the emergence or exacerbation of a large number of potential public health problems, including heat-induced mortality and increased geographical ranges of deadly diseases such as malaria and dengue fever. Loss of species biodiversity, changes in weather patterns (with increased damage from storms), sea level rise, and infrastructure costs are among the economic and ecological harms that have been identified. In addition, climate change could trigger potentially catastrophic changes in certain earth systems. Even if the probability of such disasters is small, taking action now to avert them is warranted. Uncertainty about the magnitude of the risks posed by climate change provides a strong rationale for action rather than passivity.

Estimates of the cost (excluding environmental benefits) of policies to avert climate change vary both in methodology and magnitude. However, the most reliable sets of estimates show that the standard of living of the present population would not be harmed (and might be improved) by sensible policies. Estimates based on economy-wide economic models tend to show only slight reductions in gross domestic product (GDP) from greenhouse-gas emissions reductions; alternative estimates based on technical and engineering studies of the potential for cost-effective energy-saving investments tend to show modest GDP increases. The assumptions underlying the estimates are important predictors of the size and sign of GDP effects, but in all cases the most important determinants of material standards of living in the long run are the rates of economic growth and technological progress. "No regrets" policies (such as reducing subsidies that encourage fossil fuel consumption) would improve economic performance even without factoring in the economic benefits of reduced climate change; when the economic benefits of climate protection are included in the calculations, the range of economically warranted policies expands.

The design and implementation of measures to reduce greenhouse-gas emissions makes a difference in terms of cost and efficiency. Market-based policies including provisions for international cooperation are likely to do the best job of (a) effectively reducing greenhouse-gas emissions globally, and (b) doing so with minimum disruption of other economic activity. Well-designed greenhouse-gas control policies would not cause large-scale job losses or capital flight, although it would be both feasible and appropriate to assist workers in a few sectors (such as coal mining) in making the transition to a less fossil fuel-intensive economy.

The transformation of the economy to one less dependent on burning carbon for energy would provide opportunities for expansion of employment in technologically sophisticated sectors. Similarly, reaching an international agreement to coordinate national policies to reduce greenhouse-gas emissions offers an opportunity to promote global economic progress and environmental protection simultaneously. The Montreal Protocol on Substances that Deplete the Ozone Layer shows that this kind of cooperation is possible, effective, and beneficial to all countries. It is a worthy goal for the 21st Century to achieve the same sort of international consensus on measures to protect the global climate.

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I. INTRODUCTION

Climate change looms as one of the dominant social and economic policy issues of the next century. The forecast that global climate will occupy the political spotlight for such a long time is not hyperbole. The time scale over which human activity perturbs the climate is measured in centuries. Climate change has ramifications extending beyond purely environmental concerns, including deep questions of economic growth, sustainability, intergenerational equity, and national security. The Framework Convention on Climate Change (FCCC) drawn up in Rio de Janeiro in 1992 was the first step in formulating a global response to the climate problem; the Third Conference of the Parties scheduled to take place in Kyoto in December 1997 marks another milestone in the effort of the world's nations to coordinate their policies. Because so much of the debate about what to do, when it should be done, and who should do it has been presented in terms of economic arguments, it is appropriate for Redefining Progress to devote this first Background Paper to the economics of climate change.

II. ECONOMISTS SPEAK OUT ON CLIMATE CHANGE

In a remarkable display of professional sentiment on a major policy question, over 2,500 economists from the United States recently signed a public statement calling for "preventive steps" to deal with the risks of global climate change. Eight U.S. Nobel Laureates in economics signed the statement. Signatures were solicited by sending the text of the statement, along with a cover letter from five prominent economists—Kenneth Arrow of Stanford, Robert Solow and Paul Krugman of the Massachusetts Institute of Technology, Dale Jorgenson of Harvard, and William Nordhaus of Yale—to the mailing list of the American Economic Association.[1]

ECONOMISTS' STATEMENT ON CLIMATE CHANGE

1. The review conducted by a distinguished international panel of scientists under the auspices of the Intergovernmental Panel on Climate Change has determined that "the balance of evidence suggests a discernible human influence on global climate." As economists, we believe that global climate change carries with it significant environmental, economic, social, and geopolitical risks, and that preventive steps are justified.

2. Economic studies have found that there are many potential policies to reduce greenhouse-gas emissions for which the total benefits outweigh the total costs. For the United States in particular, sound economic analysis shows that there are policy options that would slow climate change without harming American living standards, and these measures may in fact improve U.S. productivity in the longer run.

3. The most efficient approach to slowing climate change is through market-based policies. In order for the world to achieve its climatic objectives at minimum cost, a cooperative approach among nations is required—such as an international emissions trading agreement. The United States and other nations can most efficiently implement their climate policies through market mechanisms, such as carbon taxes or the auction of emissions permits. The revenues generated from such policies can effectively be used to reduce the deficit or to lower existing taxes.

1. The role of Redefining Progress as an organization was to initiate and coordinate the drafting of the Statement by the five original signers, to circulate the Statement to the membership of the AEA, and to keep track of the signatures.

The high degree of support for this statement among economists is especially significant given the public perception (in the United States at least) that the main arguments against action to avert climate change are economic—that the costs of effective policies would be large, and that delay is economically justifiable. The Economists' Statement reverses those arguments and belies the common perception of economists' views. Jokes about economists typically derive their humor from the difficulty in getting economists to agree on anything; people often say that trying to coordinate the activities of a group of economists is like herding cats. How did a strong statement calling for immediate action to protect the climate gather such widespread support from U.S. economists spanning a broad political spectrum? Part of the answer is that the professional training of economists predisposes them to be open to the idea of policy intervention to correct "negative externalities" such as environmental damage (Krugman 1997). But in the case of global climate change, the damages involve risks as well as tangible harms. To see why these risks are so important for the economic analysis of climate change, it is necessary first to review the state of scientific understanding of the problem.

III. ECONOMICS AND THE SCIENCE OF CLIMATE CHANGE

The first point of the Economists' Statement recognizes the essential contribution of the world's leading experts on climate science who made up the scientific assessment panels of the Intergovernmental Panel on Climate Change (IPCC). The basic physics of the greenhouse effect is beyond dispute; indeed, the fundamental mechanism by which anthropogenic emissions of greenhouse gases increase global temperatures was understood in the 19th Century by Arrhenius and others.[2] The presence of trace greenhouse gases in the atmosphere is what makes the Earth habitable, and these gases account for much of the variation in the surface temperatures of the inner planets of the Solar System. Without the carbon dioxide and water vapor that are the Earth's main greenhouse gases, the average surface temperature would be -18° Centigrade, below the freezing point of water, instead of the observed value of 15°C (IPCC 1990).

Working Group I of the IPCC found that "the balance of evidence suggests a discernible human influence on global climate." While this is perhaps the most quotable of Working Group I's findings, it is not the only relevant one. The IPCC Report also concluded that "a general warming is expected to lead to an increase in the occurrence of extremely hot days and a decrease in the occurrence of extremely cold days" and that "warmer temperatures will lead to a more vigorous hydrological cycle; this translates into prospects for more severe droughts and/or floods in some places and less severe droughts and/or floods in other places. Several models indicate an increase in precipitation intensity, suggesting a possibility for more extreme rainfall events….Further unexpected, large and rapid climate system changes (as have occurred in the past) are, by their nature, difficult to predict. This implies that future climate changes may also involve 'surprises.' In particular these arise from the non-linear nature of the climate system…." (IPCC 1996a, p. 7).

2. DeCanio (1994) provides some of the early scientific references.

Even though economists ordinarily are not directly involved in research in atmospheric science, oceanography, biological ecology, or paleoclimatology (some of the disciplines most heavily involved in current work on climate change), economists do have experience that can help them assimilate the findings of the natural scientists. Economists also use some of the same techniques as those employed by climatologists. Working with large mathematical models is one element of common methodology; but economists are also familiar with the effects of feedbacks in complicated systems, with the abrupt changes that characterize non-linear systems, and with the sensitivity of modeling results to choices of assumptions and parameters. Economists are aware of the way progress is made in science—through vigorous debate, peer review, and empirical testing of hypotheses. The deliberations of the IPCC (and voluminous peer-reviewed literature upon which its reports are based) bear the hallmarks of a healthy scientific process. Economists understand that the findings of Working Group I of the IPCC represent a cautious, mainstream consensus on the current state of scientific knowledge about climate change. As such, the conclusions of Working Group I form a suitable starting point for policy analysis.

The Economists' Statement recognizes that although scientific understanding of the climate system is not complete, it is appropriate to take measures now to address potential climate change. Uncertainties may be real, but they do not justify inaction. Economics can provide guidance on how to deal with the uncertainties, and has much to say regarding the effectiveness and efficiency of alternative policies. Economic reasoning and evidence can help delineate the scope of the climate change problem, and can point the way to a rational societal response. But it should always be kept in mind that sound economics is a necessary but not a sufficient condition for good policy; the decisions needed to protect future generations from climate change have ethical and cultural dimensions that extend beyond the narrow boundaries of economics.

IV. THE RISKS AND DAMAGES OF CLIMATE CHANGE

A. The Importance of Risk Management

Point 1 of the Economists' Statement asserts that "as economists, we believe that global climate change carries with it significant environmental, economic, social, and geopolitical risks, and that preventive steps are justified." Often economic analysis of an environmental policy issue uses ordinary cost-benefit analysis, and the criterion for decision is whether the directly measurable environmental benefits of the proposed pollution reduction are greater than the economic costs entailed. The case of climate change is different. Because of uncertainties in the magnitude, timing, and effects of climate change, the economic issue is more one of *risk management* than of straightforward cost-benefit comparison. The uncertainties associated with future climate change do not justify denial of the problem, but rather provide the most compelling rationale for beginning to act now to mitigate the risks and provide a reasonable margin of safety.

Even if the direction of climate change's impact on specific economic activities is unknown, it is prudent to act to avert the change. Uncertainty itself is undesirable. If there were a compulsory lottery that involved the equally probable outcomes of winning a large sum of money or suffering a large loss, most people would be willing to pay something to avoid being forced to participate. Similarly, it is reasonable to be willing to pay a modest price to avert climate change, in order to reduce the risk that an uncertain outcome will turn out badly. In fact, the climate situation is even worse than the lottery example; most of the likely impacts of climate change are negative, and some of them are potentially catastrophic. Instead of a big gain/big loss lottery, climate change is more like a game of Russian roulette, with negligible short-run benefits (of unconstrained fossil fuel consumption) weighed against the chance of huge losses (from climate-related disasters). Most people would not agree to play a game of Russian roulette for *any* sum of money. In a way, risking climate change is even more frightening than playing Russian roulette, because the risks and "benefits" are borne by different generations. The image of a game of Russian roulette being played for some trivial payoff but with the pistol pointed at the head of one's *child* is almost too gruesome to contemplate. Yet modifying the global climate without knowing the ultimate consequences is akin to just this sort of imposition of dire risk on future generations for our own transitory or illusory advantage.

The consequences of climate change would involve more than simply a small increase in average temperatures—that is why "global warming" is a misnomer for the problem. The second volume of the IPCC's recent assessment presented information on the full range of human health-related risks associated with climate change. The IPCC classified the risks as both direct and indirect. Direct risks include altered rates of heat- and cold-related illness (especially cardiovascular and respiratory diseases) and death from exposure to thermal extremes (especially heat waves) and the deaths and injuries caused by altered frequency and/or intensity of extreme weather events such as storms and floods. The indirect risks stem from disturbances of ecological systems, including changes in the range and activity of disease vectors and infective parasites, altered local ecology of water-borne and food-borne infective agents, and altered crop productivity. In addition to these indirect risks are those associated with sea level rise, social and economic dislocations, and asthma and allergic disorders caused by biological impacts of changes in air pollution including pollen and spores (IPCC 1996b). These direct and indirect threats to human health from climate change are extensive and serious. Climate change poses a massive public health problem, one no less worthy of policy attention and expenditure of resources than the control of infectious diseases or the sufferings of aging. Indeed, given the links between climate and the spread of infectious diseases, these public health problems overlap.

Some of these risks can be gauged in the light of present knowledge. For example, a warming trend could extend the range of certain "tropical" diseases such as malaria and dengue fever. These diseases have very large associated costs in terms of illness and premature mortality. According to the IPCC, "the geographical zone of potential malaria transmission in response to world temperature increases at the upper part of the IPCC-projected range (3-5°C by 2100) would increase from approximately 45% of the world population to approximately 60% by the latter half of the next century" (IPCC 1996b, p. 12). It is not easy to translate these figures into quantitative projections of increased sickness and deaths (or monetary cost estimates), because of differences in the capacities of various populations to undertake mitigation measures, differences in the response capabilities of health care infrastructures, etc., but every year 270 million people world-wide suffer from malaria and one to two million die of it. Increased malaria incidence related to local climatic change has already been observed in Rwanda, and according to one model, one million additional fatalities per year could be attributed to climate change by the middle of the next century (Patz et al. 1996; Martens et al. 1994).[3]

Another risk created by climate change is the probable loss of species biodiversity, as environmental conditions and the characteristics of local habitats change more rapidly than species can adapt. The pace of climate change is now speeding up, creating a situation in which some species' ranges of viability are moving more rapidly than the species can migrate. Even a relatively mobile species may be at risk if it is ecologically dependent on other species that cannot migrate quickly enough. The magnitude of this risk is unknown, because we do not fully understand ecosystem dynamics, and the full impact of biodiversity loss is not quantifiable with existing techniques. The value of biodiversity includes potential medical compounds, the value of not foreclosing the options of future generations, the fact that predator/prey relationships (which would be disrupted by a loss of certain species) help control diseases spread by animal vectors, and the intrinsic worth of biological diversity.

The most common market response to protect against financial losses from uncertain events is to purchase insurance. Ordinary insurance markets work by spreading localized or individual risks over a large number of cases; actuarial statistics

3. The mosquitoes carrying the parasites that cause malaria have become resistant to insecticides, and the disease itself has become resistant to the drugs traditionally used to treat it. Vaccination offers the greatest hope for future control, but a malaria vaccine is still years away (Sanderson 1992, citing Institute of Medicine, National Academy of Sciences 1991).

enable insurance providers to make a profit while paying claims when losses occur, thereby satisfying individuals' need for protection. But because climate change is global and some of the risks cover large areas or are planet-wide, this sort of insurance model does not apply.

The only way to purchase insurance against climate change is to make prudent investments now to avoid future dangers.[4] We vaccinate our children against dangerous and potentially fatal diseases, even though there is a small monetary cost to the vaccinations and a slight risk of adverse reactions. The magnitude of the potential harm of life-threatening diseases such as polio, diphtheria, or measles is so great as to warrant the financial cost and health safety risks of inoculations. Undertaking policies to avoid environmental risks, even though there may be some cost associated with those policies, is at times the preferred course of action. There is undoubtedly broad and deep support in the United States for environmental protection measures that reduce the risks of illness and death from various pollutants.

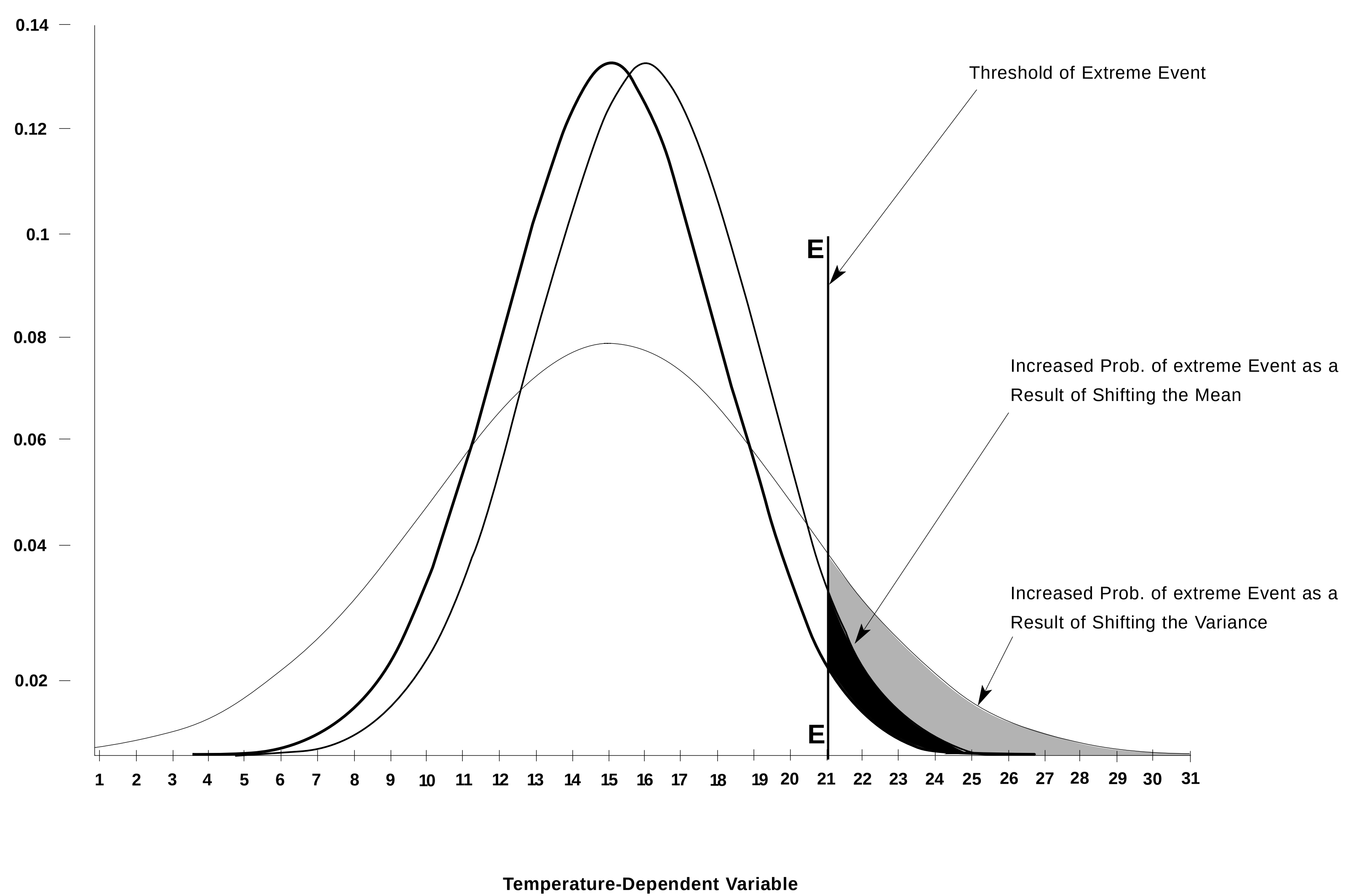
As noted above, focusing only on the expected change in average global surface temperature understates the risks of climate change. Suppose some outcome has a probability distribution of the normal shape, with the mean of the distribution depending on the concentration of greenhouse gases in the atmosphere. An example might be the daily temperature on a specific date in a particular location. Figure 1 (see page 10) shows such a distribution.[5] The vertical line EE in the figure represents the threshold of an extreme event, such as the onset of a killer heat wave. A slight increase in the mean of the distribution increases the probability of the extreme event (measured in Figure 1 by the black shaded area to the right of EE), but the increase in probability may be even greater if the variance of the distribution increases (Katz and Brown 1992; Wagner 1996). (This case is shown in Figure 1 by the sum of the two shaded areas to the right of EE.) Climate change takes the form of increased variance in the weather as well as an increase in average temperatures. Thus,

4. It is noteworthy that insurance industry executives have begun to express concern about the impact of climate change (see Leggett 1996).

5. See also IPCC (1996c), Figure 1.1.

Figure 1

EFFECTS OF SHIFTING THE MEAN OR CHANGING THE VARIANCE



even a “small” amount of climate change (if measured solely as an increase in average temperature) can trigger considerably increased probability of extreme events, particularly if the variance of the weather increases at the same time.

B. Estimates of Direct Damages

In addition to protecting against the risks of climate change, policies to reduce greenhouse-gas (GHG) emissions can also reduce some *predictable* damages from increasing global temperatures. Calculations of probable damages tend to take as their starting point the most firmly established consequences of global warming, such as rising sea levels, temperature-related changes in the demand for heating and air conditioning, health effects of increased temperature extremes, estimated changes in agricultural productivity, and water quality and availability. Current estimates of these potential damages are on the order of 1% to 2.5% of GDP[6] for a doubling of atmospheric concentrations of CO_2. Specific components of damage included in the calculations are listed by the IPCC (1996c) and its underlying references (Cline 1992; Fankhauser 1995; Nordhaus 1991; Titus 1992; Tol 1995). The different scholars who have made these estimates do not cover the same items in their lists of damages (although there is considerable overlap).

It is important to note what is *not* included in these calculations. The 1% to 2.5% of GDP range does not include damages that would result from the global warming caused by a *greater* than doubling of atmospheric CO_2 concentrations. Yet unless action is taken, atmospheric concentrations of CO_2 are projected to double by around the middle of the next century, and will continue to increase after that. Many of the damage functions underlying the estimates are non-linear, meaning that the damages could increase more than proportionally as global average temperatures rise beyond the CO_2 doubling level.[7]

6. These are the percentages of GDP for a typical industrialized country like the United States. Damage estimates as a fraction of GDP can be considerably higher for developing countries.

7. Atmospheric modeling calculations of the temperature increases associated with increased greenhouse gases are often benchmarked at a doubling of CO_2 concentrations, but the climate change process will not come to a halt when this level is reached. Hence, estimating damages based on CO_2 doubling underestimates the actual damages.

These damage estimates do not attempt to quantify the huge value of ecosystem services and natural capital (as calculated by Costanza et al. 1997, for example).

C. Catastrophic Possibilities

The damage estimates reported above also *do not assign a value to the risk of unpleasant surprises or catastrophic changes.* By definition, the full dimensions of any such surprise cannot be known ahead of time, but three main types of potential climate catastrophe have been identified by the IPCC. All are associated with non-linear responses to increases in atmospheric concentrations of greenhouse gases: (1) a runaway greenhouse effect, (2) disintegration of the West Antarctic Ice Sheet, and (3) structural changes in ocean currents.

The "runaway greenhouse effect" refers to a situation in which the warming from human GHG emissions begins to trigger additional emissions of GHGs from biological or mineralogical systems. This would lead to a rate of climate change much more rapid than suggested by current extrapolations. Positive feedbacks might include a rapid increase in natural emissions of greenhouse gases (e.g., through methane and carbon dioxide releases from melting permafrost or methane clathrates); a shutdown of major greenhouse-gas sinks (e.g., through reduced plankton activity or the death and decay of forests), or changes in atmospheric chemistry (IPCC 1996c, p. 208). The ocean-bottom methane hydrates contain roughly as much carbon as all known land reserves of fossil fuels, and release of methane from this source may play an important role during climate change (see Dickens et al. 1997 and the references cited therein).

Recent evidence shows that the Alaska tundra region has changed from being a net sink of CO_2 to a net source, raising the possibility that carbon released from the tundra could become a positive feedback to global warming (Oechel et al. 1993). Research on the response of the Antarctic ice sheets to global warming is very active, with controversy between the “stabilists” and “dynamists” over the possibility of a major melting (Sugden 1992; LeMasurier et al. 1994; Sugden et al. 1995; Horgan 1995; Schneider 1997). A number of studies suggest that changes in the pattern of ocean currents may be responsible for major climate changes measured on time scales of decades (Broecker 1995; Behl and Kennett 1996).

Even if the probability of any of these catastrophic possibilities is low, their risk value is high because the costs associated with them would be so huge. The need for prudent risk management comes to the forefront here; people are generally willing to pay to reduce the odds of unlikely but highly destructive events (residence fires, airplane crashes, nuclear power plant meltdowns). The cost of catastrophic outcomes, measured either as expected values or as peoples’ willingness to pay to avoid risking them, has to be included in a complete accounting of the damages of climate change.

Finally, social and political systems would be threatened by the effects of climate change. Climate changes that reduce the habitability of low-lying coastal areas or island states could create large numbers of refugees. Forty percent of the U.S. population lives within 50 miles of the coast; it is estimated that half the world’s population lives along ocean coastlines (Hanson and Lindh 1996). Similarly, if regional variations in rainfall patterns lead to desertification and localized famines, the number of climate refugees would be increased. Refugees are already a destabilizing factor in world politics, and large increases in their number would hardly contribute to peace. Because the effects of climate change would vary regionally, there is the possibility that international conflicts over water rights or other resources could be exacerbated. Climate change could destabilize domestic politics, even in democratic countries. Frightened populations might well be vulnerable to demagogic extremism in the event of an unexpected and painful climate crisis.

Of course, uncertainty runs in both directions. The actual economic value of some of the damages from climate change may be either lower or higher than their expected value. Future technologies may make it easier to deal with some of the potential damages; it is not inconceivable, for example, that techniques of meteorological control might be developed that could diminish the frequency or impact of severe weather events by changing the paths of storms or influencing the locations where they drop their precipitation. These possibilities do not justify inaction, however. It also may be that future medical technology will be able to treat and cure cancer easily, but this does not mean that it would be wise policy to advise youths to begin smoking. Risk aversion implies that the distress associated with an unfavorable uncertain outcome is worse than the satisfaction of a favorable uncertain outcome, and most people are risk averse. This aversion to risk constitutes an intrinsic rationale for action now to avoid the uncertainties of climate change.

V. THE COSTS OF REDUCING GREENHOUSE-GAS EMISSIONS

The second point in the Economists' Statement concerns the cost to the economy of reducing greenhouse-gas emissions. A complete appraisal of measures to limit GHG emissions has to include both the benefits of avoiding the risks and damages described above as well as the price that would have to be paid to achieve those benefits by reducing emissions. This is one reason Point 2 of the Economists' Statement refers to the "standard of living" rather than measured Gross Domestic Product—environmental goods such as climate stability have a value as surely as the ordinary goods and services purchased in the market, although the latter are counted in GDP while the former are not. Yet the political debate, at least in the United States, has tended to focus almost exclusively on the cost side of this calculation. Special interest groups that seek to block action have made inflammatory and inaccurate statements suggesting that the cost of emissions reductions would be exorbitant. For example, the Global Climate Coalition, an industry lobby group consistently opposed to U.S. commitment to binding restrictions on carbon emissions,[8] recently stated that a policy to reduce CO_2 emissions "would eliminate millions of American jobs, reduce America's ability to compete and force Americans into second-class lifestyles" (quotation reported in Brown 1996). Point 2 of the Economists' Statement suggests that the opposite is true: "there are policy options that would slow climate change without harming American living standards, and these measures may in fact improve U.S. productivity in the longer run." Understanding how the costs of climate change are being estimated is critical to making an informed decision about the policy options that are available.

Economists employ two distinct methodologies for estimating the cost of reducing greenhouse-gas emissions. These are broadly characterized as the "top-down" and

8. The Global Climate Coalition by no means represents the point of view of all U.S. industry. The more moderate International Climate Change Partnership (ICCP) stands for constructive engagement by industry in the formulation of the policy response to climate change, and includes as members such leading firms as 3M Company, AlliedSignal, AT&T, Boeing Company, Chevron, Dow, Dupont, Eastman Kodak, Enron, and General Electric (Inside EPA 1996; International Climate Change Partnership 1997). Other industry groups involved positively in the climate change debate include the World Business Council for Sustainable Development and the Business Council for Sustainable Energy.

"bottom-up" approaches. The top-down method involves creating a model of the entire economy, with equations describing the paths over time of key variables such as the GDP, population, energy prices, and the rate of technological progress. The model is then run under a base case scenario in which no action is taken to control greenhouse-gas emissions. The result of the base case is compared to cases in which alternative policy actions are taken to limit emissions, such as a carbon tax or creation of tradable emissions permits.

All of the commonly used top-down models are constructed in such a way as to include the *assumption* that reductions in greenhouse-gas emissions can only be purchased at the expense of a reduction in the output of other goods and services. In all the top-down models, the various sectors and agents in the economy are presumed to be operating in a perfectly efficient manner, so that if an additional constraint is placed on their activities (such as being required to reduce emissions of greenhouse gases), the amount of ordinary goods and services that can be produced must fall. This assumption that is central to top-down models is appropriate in some applications,[9] but it has serious drawbacks if the analysis covers decades of time.

The bottom-up method takes a different approach. Instead of assuming that existing patterns of production are optimal, this method recognizes that a variety of economic, institutional, organizational, cultural, and political barriers prevent firms and individuals from taking advantage of best-practice techniques. In particular, the bottom-up studies have focused on how much greater energy efficiency could be achieved if the barriers to cost-effective investments in energy efficiency were eliminated. Unlike the top-down studies, the bottom-up studies admit the possibility that some energy savings (and hence greenhouse-gas reductions) could be achieved without loss to the larger economy.

9. Many of these models had their origins in attempts to estimate the short-term consequences of oil price shocks such as those that occurred in the 1970s. The problem of modeling long-term effects of a gradually-phased-in climate protection policy is quite different.

A. "Top-down" Cost Estimates

A number of leading top-down model estimates were reviewed by the IPCC (1996c). Many of the results and model runs presented in the literature differ with respect to the time periods they cover, as well as other assumptions. To achieve comparability, the IPCC relied on an exercise carried out by the Energy Modeling Forum at Stanford University in which several of the main models were run under a common set of assumptions. A typical scenario estimates the consequences of a 20% reduction in emissions from 1990 levels, implemented by means of a carbon tax. The eight models for which the comparison was carried out showed GDP losses in 2010 ranging from 0.9% to 1.7%, with an average of 1.2%. The carbon tax required to achieve the 20% reduction from the baseline ranged from $50 per metric ton of carbon to $260 per metric ton, averaging $170 per metric ton.

A similar modeling exercise was conducted by an Interagency Analytical Team (IAT) of the U.S. government during 1997. In this review, three models—the Data Resources, Inc. (DRI) macroeconomic model, the Markal-Macro model, and the Second Generation Model (SGM)—were used to estimate the path of GDP under the scenario of emissions stabilized at 1990 levels in 2010 with a 10-year phase-in.[10] The DRI model showed a decrease in GDP from the baseline through 2012 followed by an increase beginning in 2013;[11] in 2010 the decrease of GDP from the baseline was about 0.4%. Markal-Macro showed a GDP loss of about 0.6% in 2010, and SGM a loss of about 0.1%. The implicit carbon prices that would bring about the 1990 emissions levels in 2010 were $95 per ton in the DRI model, $81 per ton in the SGM model, and $145 per ton in the Markal-Macro model.

10. Other assumptions made in the IAT analysis were that revenues from auction of the carbon emission permits were recycled into the economy through deficit reduction, that the energy/GDP ratio decreased at a rate of 1.25% per year, and that there was no international trading of the carbon emission permits.

11. This later expansion in GDP predicted by the DRI model is a peculiar consequence of the model's original design as a short-run forecasting tool. In this model, the projected deficit reduction from the permit revenues leads to greater investment, which eventually raises the GDP. This type of naïve Keynesian structure is not shared by most other top-down models.

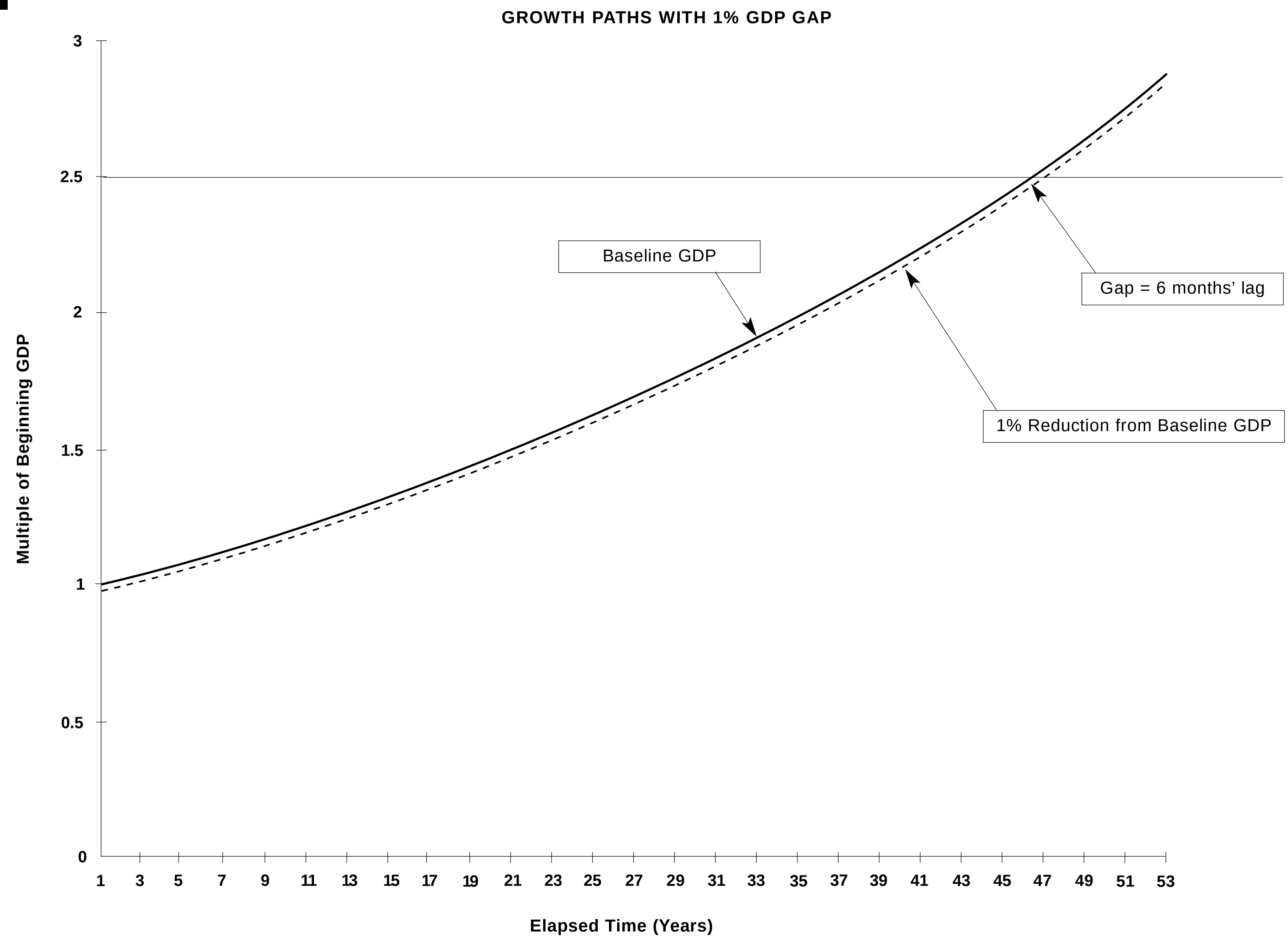
According to the IAT analysis, a $100 per ton carbon tax translates into a price increase of 26 cents per gallon of refined petroleum product (e.g., gasoline), $1.49 per thousand cubic feet of natural gas, $52.52 per ton of coal, and 2 cents per kilowatt hour of electricity. Estimated GDP losses were smaller under scenarios allowing international trading of the carbon permits (Interagency Analytical Team 1997).

It should be noted that none of these scenarios is directly comparable to the "doubling of atmospheric concentration of CO_2" case that is the basis for the direct climate change damage estimates reported in Section IV-B. It is not a simple matter to go from changes in rates of emission of greenhouse gases to changes in atmospheric concentrations. The relationship depends, among other things, on the amount of GHGs already in the atmosphere, the ability of the various carbon sinks to absorb some of the annual emissions, and the rate at which carbon dioxide from the atmosphere is mixed into the ocean. The fraction of CO_2 emissions that will be reabsorbed by terrestrial and oceanic sinks is one of the areas of greatest scientific uncertainty.

Even if the top-down modeling results are taken at face value, it is clear that the GDP losses projected by these studies are hardly disastrous. A loss of 1% of GDP is not insignificant—it amounts to about $70 billion (1992 dollars) per year at the current GDP level—yet it amounts to *less than six months of normal economic growth*. That is, a permanent loss of 1% of GDP means only about a six months' delay in achieving any particular aggregate standard of living that would be reached in the ordinary course of economic growth. Even under the conservative assumption of the top-down models that reduced emissions necessarily lead to a GDP loss, normal economic growth swamps the effects of the GHG reduction policy.

Figure 2 (see page 19) illustrates growth paths through 2050 with and without GHG reductions, under the assumption that the GHG control measures would reduce GDP by 1%. The effect of the 1% reduction is barely visible on a chart of this size; the changes in GDP are entirely dominated by the increases due to economic growth on either of the two paths. This illustrates quite dramatically the fact

Figure 2


GROWTH PATHS WITH 1% GDP GAP
Multiple of Beginning GDP
3
2.5
2
1.5
1
0.5
0
Baseline GDP
Gap = 6 months' lag
1% Reduction from Baseline GDP
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47 49 51 53
Elapsed Time (Years)

that it is the growth performance of an economy, more than anything else, that determines the evolution of the standard of living in the long run.

Other considerations point to the conclusion that a proactive policy to reduce greenhouse-gas emissions would not seriously disrupt the economy. Job reallocations caused by a reduction in fossil fuel use would be small relative to the average pace of job turnover. For example, the entire coal mining industry in the United States employed only 106,000 workers in 1995, down from 246,000 in 1980. Thus, this industry has been losing jobs at an average rate of just over 9,000 per year over the period 1980-95 *without any GHG control measures in place* (data from U.S. Bureau of the Census 1997, Table 654). Yet the U.S. economy creates about one and a half to two million net new jobs per year, and the gross number of jobs created and destroyed through the normal process of economic change is larger (Worsham 1996; U.S. Department of Labor 1996-97). If the rate of job decline in coal were to double it would still be less than 1.5% of the normal annual rate of total net job creation. Without minimizing the hardships of adjustment to displaced coal workers, this sort of incremental change in the sectoral distribution of jobs would not be difficult for the economy to absorb, and it would be sensible to include transitional support for displaced workers (such as retraining expenses) as an integral part of any national greenhouse-gas reduction policy.

It is worth bearing in mind that the aggregate number of jobs in the United States is determined in the short run primarily by the Federal Reserve's monetary policies (and the Fed's response to current and expected changes in the economy), and in the long run by structural factors such as the size and age composition of the population. Neither the short-run nor the long-run determinants of the total number of jobs have much to do with the relative prices of different types of energy. Unexpected price changes always lead to changes in the value of capital goods, and to reallocations of both capital and labor across sectors. Policy-driven fossil fuel price increases designed to reduce CO_2 emissions could be phased in gradually (to give workers and managers time to adjust), and should begin to be factored into current investment decisions (because of the eventual necessity of addressing the climate change problem). Instead of a threat to jobs, reducing the economy's dependence on fossil fuels can be seen as an investment and job-creation *opportunity*, because of the new equipment and technologies that will be required. The conversion can be accomplished without any net loss of jobs; the role of policy is to minimize transition costs and to ensure that any such costs do not fall disproportionately on narrow segments of the population such as coal industry employees.

It is also an exaggeration to claim that fossil fuel emissions reduction policies would cause massive capital flight from the industrialized economies. Annual U.S. capital outflows, including intercompany debt and reinvested earnings, has been averaging about 7% of total annual gross domestic capital formation. The flow of equity capital alone is considerably smaller, averaging about 2% of annual gross domestic capital formation over 1992-1996. (See Bureau of Economic Analysis, *Survey of Current Business*, various issues. Direct investment components were current cost values adjusted to 1992 dollars using the BEA's GDP deflator. For definitions and discussion of the data, see the article by Mataloni (1995) in the *Survey of Current Business*.)

A large portion of these capital flows are to countries that would face changes in the relative price of fossil fuel energy similar to those experienced by the United States under a climate protection treaty. On an historical cost basis, the cumulative U.S. direct investment position in Canada, Europe, and Japan was 68% of the total in 1995 (Bach 1997). Given the magnitudes of these numbers, it is not plausible that gradually-phased-in changes in the price of fossil fuels undertaken as part of a climate treaty could cause massive capital flight from the United States.

Economic research has found no convincing evidence that environmental regulations have a significant effect on businesses' locational decisions or competitiveness. The most recent and extensive survey of the literature on the relationship between environmental regulation and the competitiveness of U.S. manufacturing concluded that "there is relatively little evidence to support the hypothesis that environmental regulations have had a large adverse effect on competitiveness, however that elusive term is defined….[S]tudies attempting to measure the effect of environmental regulation on net exports, overall trade flows, and plant-location decisions have produced estimates that are either small, statistically insignificant, or not robust to tests of model specification" (Jaffe et al. 1995, pp. 157-8). A great many factors influence decisions on where to build new plants, including the availability and quality of the labor force, proximity to output markets and input sources (i.e., transportation costs), the locational preferences of management, tax considerations (other than environmental taxes), and political stability. Pollution regulations are far down on this list. Some work suggests that properly designed environmental standards may even bolster productivity (Porter 1990, 1991; Porter and van der Linde 1995; Goodstein 1997). Thus, even if the Protocol negotiated in Kyoto has differential emissions reduction requirements for developed and developing countries, it will not cause a flight of new investment to the developing countries.

B. "Bottom-up" Cost Estimates

The top-down estimates are premised on the idea that reductions in GHG emissions can only be purchased at the expense of other goods and services. An alternative picture of the economic effects of GHG emissions abatement is given by the bottom-up studies. The IPCC surveyed the literature and found a large body of evidence that substantial emissions reductions could be accomplished at a net *gain* to the economy (IPCC 1996c). In the studies surveyed by the IPCC, an emissions reduction on the order of 25% from the base year level could be achieved at zero net average cost.[12]

Since publication of the IPCC report, several new studies estimating the positive economic potential of energy-efficiency improvements have appeared. The

12. The 25% figure is the median of the different values obtained from studies with an ending point between 2000 and 2030. Some of the studies did not include options all the way up to the intersection point of the x-axis. This means that larger reductions could be achieved for negative or zero net cost.

most comprehensive of these, *Scenarios of U.S. Carbon Reductions: Potential Impacts of Energy-Efficient and Low-Carbon Technologies by 2010 and Beyond*, was prepared by researchers at five of the national laboratories—Oak Ridge National Laboratory, Lawrence Berkeley National Laboratory, Pacific Northwest National Laboratory, National Renewable Energy Laboratory, and Argonne National Laboratory (Interlaboratory Working Group on Energy-Efficient and Low-Carbon Technologies 1997). This study examines four key sectors (buildings, transportation, industry, and electric utilities) in detail, and concludes that it would be possible to reduce carbon emissions to roughly 1990 levels by 2010 at "net costs to the U.S. economy...near or below zero in this time frame."[13]

A second major new bottom-up study was carried out by a consortium of the Alliance to Save Energy, the American Council for an Energy-Efficient Economy, the Natural Resources Defense Council, the Tellus Institute, and the Union of Concerned Scientists (1997). This report, titled *Energy Innovations: A Prosperous Path to a Clean Environment*, finds that the United States could follow an "Innovation Path" that by 2010 would lead to "a national energy system that, compared to the Present Path, reduces net costs by $530 per household, reduces global warming CO_2 emissions to 10 percent below 1990 levels, and has substantially lower emissions of other harmful air pollutants." Finally, an adaptation of the U.S. Energy Information Agency's National Energy Modeling System (NEMS) model has been developed building in more dynamic assumptions about market transformation and behavioral change than originally contained in the NEMS model (Hoffman and Sylvan 1996). Running the NEMS model with these assumptions results in forecasts of GHG emissions in 2015 reduced by 13% to 39% from the NEMS baseline (the 39% reduction corresponds to a 21% reduction from 1990 emissions levels), with a GDP *gain* of between 0.3% and 0.5%.

Companies and individuals around the world already are earning profitable returns by investing in energy-saving technologies such as modern fluorescent lighting

13. The 1990 emissions levels could be reached by 2010 with a carbon price of $50/tonne, assuming that this price signal would be accompanied by "a vigorous national commitment to develop and deploy cost-effective energy-efficient and low-carbon technologies....[a]long with utility sector investments...." (Interlaboratory Working Group 1997).

systems, variable-speed motors, computer-controlled HVAC (heating, ventilation, and air-conditioning) systems, new CFC (chlorofluorocarbon)-free refrigeration and cooling systems, and improved building design. Corporate leaders are increasingly recognizing the potential for earning money while making significant GHG reductions, as indicated by participation in voluntary energy-saving programs in the United States (such as the EPA's Green Lights and Energy Star initiatives, or the DOE/EPA Climate Wise program), and by the recent announcement by Keidanren, the multisector Japanese business group, to cut its CO_2 emissions 10%-20% from 1990 levels by 2010 (*Global Environmental Change Report* 1997).

C. Towards Resolution of the Question of Costs

The existence of these two strands of literature on the cost of GHG reductions poses a problem of scientific methodology for economists. Both sets of estimates cannot be right, yet there is no clear consensus on how to make the two types of calculations consistent. Therefore, it is useful to step back from the divergent estimates in order to gain some perspective on why, in this instance, economists disagree.

The results obtained by top-down models are strongly dependent on the assumptions built into the models. A recent meta-analysis of the estimates of the costs of climate protection that were obtained from 162 runs of 16 of the most widely used models shows that almost all the variation in predicted economic impacts is accounted for by differences in eight key assumptions. These assumptions include: the availability and cost of a non-carbon "backstop" technology, the efficiency of the economy's response to price changes, the degree of inter-fuel and product substitutability, how many years are available to achieve the specified CO_2 reduction target, whether reducing CO_2 emissions would avoid some economic costs of climate change, whether reducing fossil fuel combustion would avoid other (non-climate) air pollution damages, how the carbon tax revenues are recycled into the economy, and whether "joint implementation"[14] options are available or not (Repetto and Austin 1997).

14. "Joint implementation" refers to a country such as the United States obtaining credit towards its GHG reduction target by financing an emissions-reducing project in another country.

The top-down studies also have built-in assumptions about how technology changes that tend to overstate the costs of GHG mitigations. For example, if future technological change, particularly in energy efficiency, is limited to historical rates, model estimates will not capture the effect of policies that could speed up the rate of technical progress. Investments in research and development (R&D) have high payoffs, and it is well-established that that new knowledge is a "public good" that will not be produced in socially optimal quantities without government support. A private company can capture only a portion of the economic gain that results from successful R&D activity, and this is why estimates of the social rate of return to R&D are higher than market rates of return on ordinary private investment. Table 1 (see page 26) gives a summary showing rates of return to R&D estimated by various investigators.

The average social rate of return to R&D from this table is 63.8%; the private rate of return to R&D is 31.8%.[15] Mansfield (1991) states, "[d]ozens of economists working independently with quite different sorts of models and entirely different kinds of data have found that the social rate of return from industrial innovations and R&D has been very high, frequently 40 percent or more. This is a remarkable fact, and one that policy-makers should recognize." This is why there is such a broad consensus that government should subsidize basic research. Government initiatives to increase the rates of innovation and diffusion of technologies that would help reduce greenhouse-gas emissions could substantially change the values of the technical change parameters embedded in the top-down models, and could have a positive impact on the growth performance of the economy as a whole.[16]

15. Both endpoints of ranges were included in computing the averages.

16. It can be argued that increasing R&D in the energy-efficiency sector could drain scarce scientific and technical resources from other, potentially more productive, R&D activities. (See Goulder and Schneider (1996) for a good development of this argument.) The seriousness of this problem depends on the extent to which (1) the total R&D budget for the economy is fixed, and (2) the allocation between energy-efficiency R&D and other R&D is already optimized. Neither of these conditions would appear to hold now. Indeed, we know that it is possible to increase aggregate R&D substantially; this is a policy decision having mainly to do with the funding of graduate education for scientists and engineers, and with the availability of jobs and equipment for those researchers upon completion of their degrees. The time lag for beginning to see the effects of such an effort would be three years at the most. We have the historical experience of the post-Sputnik push that demonstrates the feasibility (and benefits) of an increase in society-wide R&D. Nor is the national allocation of R&D effort optimal. Public research dollars are not allocated on the basis of their expected rate of return, even excluding the very large expenditures on military R&D (which contribute to military preparedness but do not have a direct economic return at all).

Table 1

PRIVATE AND SOCIAL RATES OF RETURN TO R&D ACTIVITY

Source	Private Rate of Return (%)	Social Rate of Return (%)
AGRICULTURE		
Griliches (1958)[1]		20.0 - 40.0
Peterson (1967)[1]		21.0 - 25.0
Schmitz-Seckler (1970)[1]		37.0 - 46.0
Griliches (1964)[1]		35.0 - 40.0
Evenson (1968)[1]		41.0 - 50.0
Evenson et al. (1979)[2]	14.4 - 87.1	45.0 - 130.0
Knutson-Tweeten (1979)[1]		28.0 - 47.0
Huffman-Evenson (1991)[1]		11.0 - 83.0
INDUSTRY		
Terleckyj (1974)[3]	28.0 - 29.0	76.0 - 107.0
Mansfeild et al. (1977)[3]	25.0	81.0
Sveikauskas (1981)[3]	10.0 - 23.0	60.0 - 73.0
Scherer (1982)		70.0 - 104.0
Mohnen-Lepine (1988)[3]	56.0	84.0
Bernstein-Nadiri (1988)	8.5 - 26.7	10.5 - 161.5
Bernstein (1989)	24.0 - 47.0	29.0 - 93.6
Goto-Suzuki (1989)	25.5	105.5
Bernstein-Nadiri (1991)[3]	14.0 - 28.0	70.0 - 84.0
Mansfeild (1991)		10.0 - 200.0
Suzuki (1993)	15.4 - 20.2	15.4 - 23.8
Nadiri-Mamuneas (1994)[4]		6.0 - 17.1
Coe-Helpman (1995)	123.0	155.0
Bernstein (1996)	12.0 - 19.1	31.7 - 183.1

1. Returns from Griliches (1992), citing Huffman-Evenson (1991).
2. In this reference, private returns are returns on R&D within the state in which the R&D originated.
3. Returns from Griliches (1992).
4. Public R&D.

Nor is government action the only influence on these rates of technological change. Progress and innovation in one area such as energy efficiency can lead to a "virtuous cycle" of further improvements, as well as to spillover benefits for productivity in general. One of the most firmly established rules of industrial engineering is that unit costs decline as total production increases. This phenomenon of learning by doing applies particularly to new technologies. Devoting management attention to a particular sphere of operations can uncover other improvements in productivity and quality that had previously gone unnoticed. Without making a judgment about which areas of an organization's activities would show the greatest returns to this kind of design review, it has been documented that paying attention to energy efficiency issues often has unanticipated collateral benefits (Romm 1994).

Recent experience suggests that prospective, model-based estimates of the cost of environmental protection measures have been too high. Before passage of the Clean Air Act Amendments of 1990 (which included a system of tradable SO_2 permits), model-based estimates of the cost of the proposed permits that would be required to meet the Act's emissions reduction targets were high, as much as $1,500 per ton of SO_2. Forecasts of the marginal costs of emissions reductions under imperfect trading were in the $2,000-$4,000 per ton range for a number of utilities. Industry estimates from the mid-eighties of marginal costs without emissions trading were of the same magnitude. In actuality, the permits have traded at about one-tenth that level; in 1996, the allowances were trading at less than $100 per ton. The early estimates of costs were so much higher than the current price of the permits for a number of reasons. Some of the pre-CAAA estimates did not allow full trading of permits; competition and innovation have lowered transportation costs and the cost of scrubbers; SO_2 emissions did not grow between 1990 and 1995 (when the new CAAA requirements went into effect) as projected; and the timing of the program and other features of the regulatory design act to lower the cost of the permits in the near term (Bohi and Burtraw 1997).[17] This

17. There is some evidence from experiments performed under laboratory conditions with college students that the unusual type of auction used by the EPA to transfer SO_2 allowances between buyers and sellers may depress the transactions price somewhat (Cason and Plott 1996). However, in the experiments the price distortion was small in percentage terms, and even if this effect were operating in the real auction market, it cannot account for more than a small fraction of the discrepancy between the ex ante estimates and ex post prices.

lower-than-expected cost of the SO_2 reductions does not mean that there were (and will be) no cost to obtaining the economic and environmental benefits of the reductions. Rather, as Bohi and Burtraw state, "[e]ngineers and economists have been given another lesson in humility in projecting the benefits and costs of environmental regulation" (1997, p. 74).

Another significant example of the overestimation of the cost and difficulty of environmental protection is the case of ozone-depleting substances (ODSs). In the early 1980s, best available studies projected that only a fraction of CFC use could be replaced by substitute technologies. The RAND Corporation, in work carried out for the U.S. Enviromental Protection Agency, estimated that "the most promising set of mandatory controls could reduce cumulative emissions [of CFCs] over the period [1980-1990] by perhaps 15 percent" (Palmer et al. 1980). A subsequent study concluded that the technical options available then had the potential to reduce CFC emissions by only about one-third (Mooz et al. 1982). There was even discussion of excluding CFC-113 from the Montreal Protocol, because this solvent was considered vital for electronics manufacture and no known substitutes were available (Benedick 1991).

Estimates made in 1988, just after the signing of the Montreal Protocol, projected that it would cost $3.55 per kilogram of CFC reductions to achieve the 50% cutback in CFC production and consumption required by the year 2000 under the Protocol. By 1992, the estimated cost of reductions had fallen to $2.20 per kg. for a *complete* phaseout by the year 2000. In 1993, the estimated cost for an *accelerated* complete phaseout by 1996 was $2.45 per kg., hardly different from the estimate only a year earlier for a longer phaseout period (Cook 1996). Looking at the issue in a slightly different way, Hammitt (1997) found that the actual reductions in CFC-11 and CFC-12 usage have been much greater as the prices of these compounds have increased than had been estimated before the fact. This means that the actual marginal cost of the phaseout has been considerably lower for each level of reduction than had been forecast.[18] As Hammitt observes, "estimated

18. CFC-11 and CFC-12 were quantitatively the most important of the ozone-depleting substances covered by the Montreal Protocol. Hammitt found that the ex ante and ex post costs of CFC-113 phaseout were much closer.

costs of prospective regulations can be substantially overestimated, and...uncertainty bounds may not be wide enough to account for this bias. Cost overestimates appear to be more likely when compliance involves the innovation and diffusion of a technology not currently in commerce, for which estimates of cost, effectiveness, and susceptibility to regulation on health or other grounds are necessarily highly uncertain" (1997, p. 15).

Only after the signing of the Montreal Protocol sent the unambiguous signal that use of ODSs had to be drastically reduced did the floodgates of technological change open. By 1997, almost all ODS production has been phased out in the industrialized countries with little impact on consumers, no decline in living standards, and no deterioration of lifestyles. In many cases, profitable new technologies have replaced CFCs while improving product quality. No one would argue the CFC phaseout has been effortless or easy; on the contrary, industrial leadership in Japan, Europe, the United States, and the other OECD (Organization of Economic Cooperation and Development) countries, in cooperation with the developing countries of the world, was essential for success of the phaseout. The point is that the early estimates of the cost of replacing ozone-depleting substances far exceeded the actual cost of the alternatives.

To summarize, the economics literature spans a variety of estimates of the cost of reducing greenhouse-gas emissions. These estimates range from modest (on the order of one percent of GDP for a 20% reduction in emissions) to zero or even negative (in the bottom-up estimates of the energy savings that could be achieved at a profit). Narrowing the range of these estimates is one of the most active areas of research on climate economics. But even without sharper estimates of the cost of potential mitigation measures, it can safely be concluded that measures to slow the buildup of greenhouse gases in the atmosphere would not devastate the economy. Claims that meaningful GHG reduction measures would impose unacceptably high costs are exaggerated and fall outside the mainstream of economic thought. The key to minimizing the adjustments that will accompany the inevitable shift away from dependence on fossil fuels is to adopt a market-based

GHG reduction strategy and speed up the development and adoption of the energy-efficient technologies of the future.

D. Comparing Costs and Benefits

It might seem that the next natural step in the economic analysis of climate change would be to compare the costs of policies to slow the growth of green-house-gas emissions with the benefits of averting or diminishing climate change. This effort has begun and is commonly referred to as "integrated assessment" (IA). The previous discussion gives some indication of the difficulty of integrated assessment, however. If the biggest concerns about climate change take the form of risks as opposed to known damages, and if economists are in disagreement about whether GHG reductions can be obtained at zero net cost or are only available at a price of some reduction in GDP, then it is not surprising that the balancing of costs and benefits of climate protection policies is not a simple and straightforward matter. In addition, there are other, subtler and more technical, problems that plague the integrated assessment enterprise.

In the case of a problem such as climate change that unfolds over a time scale of decades, some method has to be used to compare costs and benefits accruing at different points in time. The standard method for doing this in ordinary cost-benefit analysis is to "discount" future costs and benefits, that is, to convert the dollar estimates of the future costs or benefits to present values using a suitable discount rate. When applied to climate economics, this procedure encounters severe difficulties for a number of reasons. First and most important is the fact that the costs of climate change and of the measures that might be taken to avert it will, to a large extent, be incurred by members of different generations. Actions taken now to begin reducing GHG emissions may be costly for people who are alive today, while the effects of climate change will be felt most acutely by those not yet born. It is a fundamental limitation of economic analysis that the utilities of different individuals cannot be compared. There is no way, within economics, of asserting positively that the value of an extra dollar of consumption to one person is equivalent to or different from the loss of a dollar of consumption goods by another person. One of the people being compared may be on the brink of starvation while the other is a millionaire; or one may be an ascetic for whom worldly goods mean nothing while the other is a staunch materialist. This problem is usually swept under the rug in policy analysis by focusing on economic aggregates such as GDP (with policies that increase national income generally preferred to policies that reduce it), but in dealing with effects felt across generations, comparing the utilities of different individuals cannot be avoided. Use of a market discount rate to evaluate an ordinary personal investment decision is fundamentally different from using a discount rate to compare the "value" of an environmental disaster that happens in our grandchildren's time to the cost of investments today that could avert that disaster.

One of the ways integrated assessment models seek to get around this difficulty is through construction of a hypothetical social welfare function, the maximization of which is deemed to be the objective of an imaginary social planner or the government. Typically, this social welfare function is the discounted sum of the consumption of all individuals over some, possibly infinite, time horizon.[19] Technical methods are available for solving such problems mathematically (Barro and Sala-i-Martin 1995), but the application of these methods to the climate problem encounters unexpected difficulties. Chief among these is that there is an interaction between the climate and other components of the utility of consumers that has to be taken into account in solving the mathematical optimization problem. In the solution of the optimization problem, the discount rate is endogenously determined by factors such as the weight assigned to the value of consumption by people at different income levels[20] and the rate of technical progress in the economy. The fact that the environment matters for peoples' material welfare thus influences

19. The question of whether a measure of total consumption or of per capita consumption is to be maximized is open. Does social welfare increase with population, holding per capita income constant? This issue is beyond the scope of this paper.

20. When the time horizon stretches across generations, the problem of interpersonal comparison of utilities reappears. It is inescapable in climate policy analysis.

both the discount rate and the optimal policy path. This subtle interaction has been recognized in the literature,[21] but it has not yet been built into the numerical models commonly used for integrated assessments.

Another recently developed approach to the problem of intergenerational comparisons draws on "overlapping generations" (OG) models. In OG models, successive generations transact with each other through devices such as the younger generation's accumulating capital which is later used to support retirement by collecting rents for use of the capital from the succeeding generation. Models of this type allow the weights assigned to different generations' well-being to be specified explicitly, as a value judgment outside the modeling context. When this is done in a way that treats all generations equally from a moral standpoint, the discount rate and optimal path are quite different (and more aggressively protective of the environment) from what they would be under conventional discounting assumptions (Howarth 1996).

These issues are necessarily abstruse and technical. Development of integrated assessment models for evaluation of alternative climate policies is one of the most active frontiers of economic research. Uncertainties that are planetary in scope, discernible human impacts on the global environment, and a policy horizon that extends over decades or centuries are new problems for humanity, and the analytical methods required to deal with them intelligently are still being developed. Also, it should not be forgotten that global climate change affects much more than economics. In addition to the ethical issues intrinsic to comparing the material well-being of different generations, the whole question of the relationship of humankind to the rest of the natural world is open. The view that humans as a species have no particular claim to precedence contends with the conception that

21. Amano (1997) gives a particularly succinct discussion, including references; see also Bovenberg and Smulders (1995, 1996). Tol (1994) has shown that including environment in the utility function changes the optimal path in Nordhaus' DICE model (1994), leading to greater greenhouse-gas reductions than those otherwise calculated as optimal. Recognition that the interest rate is a function of the choice of the economy's long-run growth path goes back to the original literature on the "Golden Rule of Capital Accumulation" (Phelps 1966). In simple models with fixed savings rates, the discount rate takes on a particular value if the economy is on the steady-state growth path for which per capita consumption is maximized.

we have a stewardship role and a unique responsibility for the welfare of the Earth; others hold that the natural world is entirely subordinate to human concerns. The "value" of the environmental legacy we bequeath to future generations can be visualized in other than dollar terms. Happiness and suffering have dimensions that transcend economic welfare. For all these reasons, purely economic comparisons of alternative climate policy paths should be viewed with great circumspection. What economics can tell us is that initial steps in the direction of atmospheric stabilization are worth taking now. Undoubtedly some "no regrets" GHG reductions are possible with current technology; without question there is real potential for technological progress in energy efficiency and power generation; and there is no doubt that almost everyone values the environment. These points of consensus can form the starting point for policy design.

VI. INTERNATIONAL COOPERATION AND THE CHOICE OF POLICY INSTRUMENTS MATTER

Point 3 of the Economists' Statement calls attention to the advantages of using market-based policies to reduce GHG emissions, and to the value of international cooperation in achieving the world's climate policy goals. Economic analysis is unequivocal that the kinds of policies implemented to achieve any particular GHG emissions reduction target will have a significant impact on the costs. At one end of the spectrum, mandating particular technologies on a facility-by-facility basis (the traditional "command and control" style of regulation) would be the most expensive way to achieve any particular emissions reduction target. At the other end of the spectrum, eliminating distortionary subsidies that actually encourage greenhouse-gas emissions would improve aggregate economic performance even if there were no benefit to slowing the pace of global warming.

Economists since Pigou have understood that taxes on pollution or other activities that have negative external effects can improve general economic welfare. In the case of greenhouse-gas emissions, the most appropriate tax would be a charge on the emission of carbon dioxide or other greenhouse gases proportional to their global warming potential. Such a tax is often referred to as a "carbon tax," although this is really a shorthand phrase to describe a tax on greenhouse-gas emissions of all types. The advantage of a carbon tax is that it conveys information about the adverse effects of an activity (such as burning fossil fuels) in the price of the activity, thereby allowing the decentralized decision-makers to determine their own arrangements for best using their resources to pursue their own ends. Pricing the externality with a carbon tax allows the market and the environment to be mutually supportive—market activities will be guided, as if by Adam Smith's metaphorical invisible hand, to take environmental values into account.

The same marriage of market forces and environmental protection can be accomplished through government issuance of permits to emit greenhouse gases. The government can determine the desired level of emissions on scientific grounds (with a goal of achieving a given atmospheric concentration of greenhouse gases by a particular date, for example) and issue permits that will allow that goal to be met. The permits would be tradable, and would have a price that reflects the cost of meeting the emissions targets in the most economical way. The number of permits could be varied as new scientific information on the effects of climate change is obtained.

In either case, the government can use the tax revenues (or the proceeds from auctioning the permits) to reduce other taxes or to reduce the deficit. The choice will depend on the political process shaping public finance; economists are in agreement that judicious use of the tax or permit revenues can reduce the impact of the environmental protection measures on the rest of the economy.[22]

For similar reasons, international cooperation is a way of achieving global climate objectives at minimum cost. The cost of emissions reductions varies widely across countries, sectors, and activities. Construction of more-efficient rather than less-efficient electricity generation facilities in China will reduce atmospheric greenhouse-gas loadings as surely as removal of an equal amount of CO_2 through actions taken in the United States. The cost of reducing the Chinese power plant emissions may be much less than the cost of equivalent emissions reductions in the United States. If both countries can cooperate, a given emissions reduction target can be reached at a lower cost than if each country were to act on its own.

Cost minimization is not the only reason for seeking international agreement in climate policy. Growth and equity also provide a basis for multilateral action. World-wide economic growth is beneficial for all countries; increased productivity in developing countries raises demand for the exports of developed countries, and creates the kinds of goods and services consumers in the developed countries

22. Some economists have argued that the use of carbon tax or permit revenues to reduce other distortionary taxes could yield sufficient economic benefits to produce a net gain even without taking account of the environmental benefits of slowing global climate change. This so-called “double dividend” hypothesis (double dividend because there is an economic benefit from tax reform in addition to the environmental benefit) is controversial. What is not in dispute, however, is that the use of the tax or permit revenues to reduce other distortionary taxes will reduce the net cost of the emissions reductions (Hamond et al. 1997).

wish to buy. If environmental objectives can be met through policies that stimulate growth, everyone benefits. Thus, international cooperation to assure that environmental protection measures are consistent with the development aspirations of the poorer countries will be globally beneficial in the long run. An international emissions trading agreement of the type visualized in the Economists' Statement is one kind of mechanism that would promote both efficiency and fairness.

One roadblock to negotiating a successful climate protection agreement is the concern expressed by some in the developed countries over whether developing nations will adhere to a schedule of GHG reductions similar to that of the already-industrialized countries. It is important to keep in mind that although it is projected that developing countries' annual GHG emissions will match those of the OECD countries by 2020 (IPCC 1996c), the large majority of emissions to date have originated from the developed countries. On a cumulative basis, the OECD countries plus the former Soviet Union have contributed 67% of total global CO_2 emissions since 1800.[23] A principle of international equity specifying some sort of cumulative emissions budget for countries (depending on their size, of course) would produce incentives for earlier cuts in emissions by developed countries than by developing countries. It is working out the details and specifics of a global agreement that will call for patience and ingenuity, and some period of learning, institution building, and additional negotiation is likely to be required. It should be kept in mind that neither China nor India signed the original Montreal Protocol in 1987 because they feared that reductions in CFCs would set back their economic development; yet both countries joined the Protocol after the London Amendment in 1990 established a very modest (but symbolically important) Multilateral Fund to compensate them for the incremental costs of adherence to the Protocol.

Just as stabilization of the climate can most effectively be accomplished through a coordinated climate policy involving all the major economies of the world, coop-

23. The calculation of Grubler and Nakicenovic (1991) is cited by the IPCC (1996c). The time period covered is 1800-1988.

eration in the design of that policy is the clearest way to ensure that technology transfer and trade expansion are helped rather than hindered by the environmental control measures. The global environment can be a source of contention or cooperation among nations—contention if climate crises exacerbate international tensions that already exist, cooperation if the interests of all parties are taken into account and respected. The Montreal Protocol shows that cooperation is possible, effective, and mutually beneficial. It is a worthy goal for the 21st Century to seek the same sort of international consensus on measures to protect the global climate.

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