ECONOMIC IMPLICATIONS OF GREENHOUSE GAS POLICY

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ABSTRACT

This paper summarizes the debate on the costs and benefits of regional and global action to reduce future emissions of greenhouse gases. The paper also presents new evidence on possible future global emissions of carbon dioxide from burning fossil fuels where these emissions are disaggregated by major developed and developing country regions. The basis of the projections is a global simulation model called the G-Cubed model. Given these projections of future emissions, the model is used to estimate the size of carbon taxes necessary to stabilize emissions within each region in the year 2000 at the levels of emissions in 1990. It is shown that the costs of stabilizing carbon dioxide emissions vary across countries when each country stabilizes its own emissions at a 1990 level. These differences in costs reflect differences in the energy intensity of production, differences in the source of energy generation, differences in projections of population growth and different projections of productivity growth.

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1 Introduction

International concern about rising levels of greenhouse gas emissions and the implications for increasing global temperatures led to the signing of the U.N. Framework Convention on Climate Change (UNFCCC) at the United Nations Conference on Environment and Development, held in Rio de Janerio in June 1992. This convention was signed by more than 150 countries and became legally binding in March 1994. Among the initial commitments made in Rio was the proposal that developed countries would aim to target greenhouse gas emissions in the year 2000 at the levels of 1990. Given this broad guideline, the convention required certain countries to submit a “National Action Plan” to outline the amount of greenhouse gas emissions that they would allow in future years and specify the policies to be implemented to mitigate these greenhouse gas emissions. These national action plans were to reviewed by the “Conference of the Parties” (the supreme body of the UNFCCC). After the Conference of the Parties review, the UNFCCC requires countries to move from the basis of general principles to specific targets for greenhouse emission to which signatories would commit.

The first meeting of the conference of the Parties was held in Berlin in late March 1995. At this meeting the “Berlin Mandate” was adopted. The Berlin Mandate acknowledged that the commitment of developed countries to take measures aimed at returning their greenhouse gas emissions to 1990 levels by the year 2000 was not adequate to achieve the Convention's objective. To allow for this slippage in commitment by developed economies, the meeting established a process that would enable the Parties to take appropriate action for the period beyond 2000 up to the year 2020. The meeting did not introduce any new commitments for developing countries. The outcome of the conference suggests that developed economies are not undertaking any serious attempts to mitigate greenhouse gas emissions in the foreseeable future.

In parallel with the political activity related to greenhouse gas emissions, over the past few years the volume of research on the economics of global warming has exploded.[2] The literature now covers topics ranging from the optimal rate of warming to the distributional effects of greenhouse gas[3] control policies on specific types of households within different countries . Particularly intense effort has focused on measuring the cost of slowing climate change by reducing greenhouse gas emissions.[4] Indeed, much of this work has focused on a single topic: computing the carbon tax needed to hold carbon dioxide emissions at their 1990 levels.[5] Recently focus has also shifted to analyzing the degree to which unilateral action by a country to reduce emissions of greenhouse gases may be offset by changes in international flows of goods and capital. In this paper, however, we step back from the debate about particular numerical results and attempt to summarize the most important qualitative findings in literature to date. We begin with a brief discussion of global warming itself and then turn to summaries of what is known about the benefits and costs of reducing the rate of warming with a focus on countries in

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[2] For an overview of the economics of global warming see Cline (1992), Nordhaus (1991a) or Schelling (1992).

[3] Gases which contribute to the greenhouse effect include carbon dioxide, methane, nitrous oxide, chloroflurocarbons and others.

[4] See Hoeller, Dean and Nicolaisen (1990), Nordhaus (1991b), or Energy Modeling Forum (1992) for surveys of estimates of the cost of reducing greenhouse gas emissions.

[5] A carbon tax would be applied to fossil fuels in proportion to the carbon dioxide they produce when burned. Nordhaus (1979) proposed this as means of taxing the externality (global warming) produced by users of fossil fuels.

the Pacific area.

The issues surrounding unilateral versus multilateral action by countries to address the problem of rising emissions of greenhouse gases is part of a larger debate on the role of trade in goods and factor flows in mitigating environmental policy in general. A country adopting relatively strict environmental standards will increase the costs of its domestic firms and may harm their ability to compete with overseas rivals. One effect of this may be to cause dirty industries to migrate to countries with lax environmental regulation. Kalt (1985), for example, has argued that standard trade theory predicts that countries with low environmental standards will have a comparative advantage in production of dirty goods and so might be expected to produce relatively more of the world's most polluting products.

More recently this view has become known as the "Pollution Havens" hypothesis in recognition of the possibility that developing countries might deliberately choose to have low environmental standards in order to attract foreign investment. A large literature has developed on the link between environmental regulations and firm location, and has been surveyed by Levinson (1994). To date, most evidence seems to suggest that individual firms are not very likely to relocate in order to avoid regulations because other aspects of their location decision, such as labor costs, tax rates and infrastructure are far more important.

Quantitative estimates of the effects of greenhouse gas policies have been undertaken in a range of single country or multi-country large scale economic models. Although providing insight into the question of the direct impacts of greenhouse gas policy these models have been less satisfactory at answering the questions about “leakage” of the policy in one country to other countries. This inadequacy is because the model either: focus on a single country (Jorgenson and Wilcoxen (1991a,b) and Goulder (1991)); have multiple regions but no industrial disaggregation (Edmonds and Reilly (1983), Barnes, Edmonds and Reilly (1992), Cline (1989), and Manne and Richels (1990,1992)); or do not have complete integration of international asset flows and exchange rate determination (Whalley and Wigle (1990), Rutherford (1992), Felder and Rutherford (1992), and Burniaux, Martin, Nicholetti and Martins (1991a,b)). An exception is the G-Cubed multi-country model developed by McKibbin and Wilcoxen (1994) that has a full integration of trade and financial flows between regions of the world. Using this framework, the authors found that a carbon tax would produce little redirection of trade in either the short or long run. In most economies, electric power generation and local transportation are by far the most carbon-intensive activities and both are largely non-traded. We found, however, that the manner in which revenue from the tax is used does have a substantial effect on GDP. The magnitude of the effect also varies across countries since the role of coal as a traded goods varies significantly between the United States and a country such as Australia in which around 80% of coal produced is exported.

To focus more attention on some of the key issues raised in this paper we present some results from the G-CUBED multi-country model below. The first is a summary of the baseline projections of the model. These baseline projections are crucial for determining the future path of global emissions. We then present illustrative calculations of the size of taxes necessary to stabilize greenhouse gas emission in the global economy by the year 2000.

2. BACKGROUND

The Earth is in dynamic radiative balance with the Sun, absorbing high-frequency visible light radiation and ultraviolet radiation and re-emitting low-frequency infrared radiation. However, unlike the Moon, which maintains radiative balance at an average surface temperature of about -18°C, the Earth has an atmosphere, whose naturally-occuring greenhouse effect keeps the Earth 33°C warmer than it would otherwise be. The atmosphere's greenhouse gases (GHGs) – mainly water vapor, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) – absorb the outgoing infrared radiation and re-emit it, warming the Earth's surface and lower atmosphere to an average of about 15°C. These GHGs thus play a crucial role in determining the Earth's climate.

Over long periods of time, the gases in the atmosphere are in dynamic equilbrium with concentrations in the oceans and biosphere. However, since the onset of the industrial revolution, human activities – mainly fossil fuel combustion and land use changes – have greatly increased atmospheric GHG concentrations. Atmospheric CO_2 concentrations (the most important GHG), for example, have risen by nearly 30%; and half of this increase has occurred since 1960, as developed countries continue their heavy reliance upon fossil fuels and the developing countries – particularly China and India – undergo rapid industrialization. At present rates of emission, carbon dioxide accounts for about half the potential increase in temperature due to greenhouse gases, while other gases account for the remainder (Houghton and Woodwell, 1989).

The basic science and emission trends are well-known. Nevertheless, there remains a great deal of uncertainty about the extent and timing of human induced warming. Even though average global temperatures have increased by 0.3°C to 0.6°C since the late nineteenth century, research has not yet established a firm, direct link between increased atmospheric GHG concentrations and higher temperatures in this century.[6] . Despite these uncertainties, considerable research suggests that a doubling of carbon-equivalent GHG concentrations could ultimately raise global average temperatures by 1.5°C to 4°C, with uncertain but potentially widespread ecological and economic consequences. The consequences of global warming could be severe. It might change patterns of precipitation, cause the sea level to rise, increase the frequency of hurricanes and other violent storms, or increase the probability of various catastrophes.

Most industrial emissions of carbon dioxide have been by industrial countries although emissions from developing countries are rising quickly. Future projections are detailed in section 5 below. A snapshot of the current contributing countries is given in Table 1.

[6] Schneider (1989) argues that historical data indicate that global temperatures have risen by 0.5 degrees centigrade during the past 100 years, and that the rate of increase has been accelerating . This is subject to dispute. Solow (1990) presents a strong case against the position that a rapid acceleration global warming has already been observed.

Table 1: Industrial Emissions of Carbon by Countries in 1991

Country	Total Carbon Emissions (million Metric tons)	Rank
United States	1,345	1
Former Soviet Union	977	2
China	694	3
Japan	298	4
Germany	264	5
India	192	6
United Kingdom	157	7
Iraq	142	8
Canada	112	9
Italy	110	10
Korea	72	15
Australia	71	16
Indonesia	46	23
Thailand	28	30
Malaysia	17	38
Philippines	12	47

Source: World Resources (1994) (page 202) and authors calculations

3. THE BENEFIT OF SLOWING GLOBAL WARMING

We begin our economic analysis with the simple observation that emissions contributing to global warming are an externality. Thus, there is a *prima facie* case that the current rate of emissions is not optimal. Determining the optimal path for current and future emissions requires an assessment and balancing of the costs and benefits of controlling the marginal unit of each GHG. To date, most economic research on climate change has been devoted to determination of control costs (to be discussed in the next section). Less work has been done on determining the benefits of slowing climate change by reducing emissions, largely because of the great uncertainties regarding impacts. Nevertheless, the literature on climate change impacts is expanding rapidly as research teams have formed to grapple with the integrated assessment of long-run emissions trends, concentrations, climate change, and ecological and economic impacts. Much of the recent research is summarized in the forthcoming documentation of the Intergovernmental Panel on Climate Change (IPCC) Scientific Assessment (Working Groups 2 and 3).

Virtually all empirical work on the benefits of slower warming has been done by the US Environmental Protection Agency (See Environmental Protection Agency, 1988). Nordhaus has (1991a) refined EPA's estimates and constructed an overall measure of the effect of global warming on the United States. Taking account of the effect of warming on agriculture, sea level rise, energy use and other activities, he found that the three degree temperature increase expected for a doubling of the concentration of carbon dioxide in the atmosphere would impose costs equal to about 0.28% of U.S. gross national product. Rounding up to include costs he had been unable to measure, such as those associated with preferences for cooler weather, Nordhaus suggested that the actual cost was probably about 1% or at most 2% of U.S. output.

Following up on Nordhaus' work, Peck and Teisberg (1992b) noted that the actual increase in temperature could be lower or substantially higher than three degrees. Moreover, even if the three degree figure is correct for doubling the concentration of carbon dioxide, unchecked emissions could produce far greater concentrations and raise global temperatures far more than three degrees.[7] Peck and Teisberg also observed that the damage due to global warming might depend on the rate of warming in addition to the absolute change in temperature.

Using CETA,[8] a model they developed for cost benefit analysis of carbon dioxide control policies, Peck and Teisberg calculated the implicit damage function that would be required for a policy of stabilizing emissions at 1990 rates to be optimal. They found that damages would have to be cubic in temperature and two to four times higher than Nordhaus' results (4-6% of output for a three degree warming instead of 2%). If the true damages were less severe then holding emissions constant would cost far more than the benefits it would provide.

Peck and Teisberg also point out that the carbon taxes required to hold emissions constant would be inefficient. The cost of emitting an additional ton of carbon dioxide is the present value of the damages it produces over the time it remains in the atmosphere. Since this can be a hundred years or more, the marginal cost of emissions must be very similar from one year to the next. Efficiency requires that the present value of these costs be equal across time. However, without an effective international agreement on curbing carbon dioxide emissions, fossil fuel use (and hence carbon emissions) are likely to rise sharply for several decades before increasing

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[7] Schelling (1992) calculated that burning all current reserves of fossil fuels could double the concentration of CO_2 at least three times.

[8] CETA and other models discussed below are described in the Appendix.

scarcity and the availability of inexpensive alternative sources of energy lead to falling fossil fuel consumption. Holding emissions constant would require carbon taxes that rise rapidly and then fall, which would fail to equate the present value of the marginal costs of control over time.

Both Nordhaus and Peck and Teisberg conclude that current evidence on the benefits of slowing warming only justifies low cost policies. A contrasting view is that of Cline (1992), who argues that increasing the period of analysis to several centuries causes the benefits of slowing greenhouse emissions to become much larger. Since these benefits are obtained far in the future, however, the rate of discount becomes important. Even under Cline's analysis, high-cost abatement policies can only be justified if the discount rate is very low.

More research is needed on quantifying the effects of higher temperatures. At present, even the sign of the effect of warming on agriculture is not certain: higher carbon dioxide concentrations would stimulate the growth of some crops. Moreover, since the changes in temperature and precipitation produced by warming will vary across regions, much of the cost will be associated with the movement of climate sensitive activities from one region to another. Finally, it is likely that people have preferences over climates and temperatures but these have not been quantified.

4. THE COST OF SLOWING GLOBAL WARMING

Far more work has been done on the cost of policies designed to slow global warming by reducing greenhouse gas emissions. Many policies have been proposed: stimulating energy conservation, taxing emissions of carbon dioxide, taxing energy use, adopting an international system of marketable permits for carbon dioxide emissions, reforestation of temperate regions, ceasing deforestation of tropical regions, more rapid elimination of the use of chloroflurocarbons, and accelerated development of energy sources that do not generate carbon dioxide emissions are a few examples.[9] However, the policy receiving the most attention to date has been a carbon tax applied to fossil fuels.

A carbon tax was first proposed by Nordhaus (1979). It would be applied to fossil fuels used for combustion in proportion to the carbon dioxide the fuels emit when burned. From the standpoint of economic efficiency, a carbon tax is the ideal way to reduce carbon dioxide emissions because it is very close to a tax on the externality itself. It would stimulate users to substitute other inputs for fossil fuels and to substitute fuels with lower carbon content, such as natural gas, for high-carbon fuels such as coal.

Many estimates of the impact of carbon taxes are now available. Detailed surveys are given by Hoeller, Dean and Nicolaisen (1991), Nordhaus (1991b) and the Energy Modeling Forum (1992). Much disagreement remains on how large a carbon tax must be to achieve various emissions goals. Nordhaus summarized the findings of nine prominent studies by pooling simulation results from all nine and then regressing percentage reductions in carbon emissions on carbon taxes. The estimated relationship he obtained suggests that a $100 per ton tax would, on average, reduce carbon emissions by 43% relative to their uncontrolled level. For smaller taxes the relationship is close to linear (a $50 tax produces a 25% reduction), but for larger taxes the change in emissions is much less than linear: a $150 dollar tax produces only a 56% reduction.

Although the models surveyed by Nordhaus and others produce a range of results, most of the differences can be traced to a few key assumptions. Of particular importance are factors

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[9] See Environmental Protection Agency (1989) or Nordhaus (1991a) for a comprehensive discussion.

determining the baseline path of carbon emissions. The focus of most studies has been on calculating the carbon tax needed to return emissions to a particular level, such as that which prevailed in 1990. The difficulty of holding carbon emissions fixed far into the future depends heavily on how much emissions would have grown in the absence of a tax. Thus, the tax needed to achieve a fixed target will increase with uncontrolled baseline emissions. Baseline emissions, in turn, are determined by population growth, capital formation and neutral technical change; by any energy-saving or energy-using biases in technical change; and by substitution away from fossil fuels if exhaustion of reserves drives prices up in the future.

Biases in technical change have been a significant source of controversy. Engineering studies sometimes suggest that there have been substantial improvements in energy efficiency over the last few decades beyond what would arise from price-induced substitution. Manne and Richels included this effect in Global 2100 and referred to it as the rate of "autonomous energy efficiency improvements" or AEEI. Their value for AEEI ranges from 0 to 1 percent annually and varies over time and across regions. An AEEI of 1 implies that annual energy requirements per unit of output drop by one percent per year. The true value for AEEI is still a subject of debate. Econometric analysis by Hogan and Jorgenson (1991) suggests that the biases of technical change vary across industries and that for many industries technical change is actually energy-using, which would imply that AEEI should really be negative. In any case AEEI plays a very important role: Manne and Richels have shown that high values of AEEI lead to very slow growth of baseline carbon emissions and hence to low carbon taxes for any given target while low values of AEEI lead to rapid growth in baseline emissions and high carbon taxes. By the year 2100, according to Manne and Richels, the level of baseline emissions under a pessimistic view of AEEI is several hundred percent higher than under a more optimistic view.

Other factors having an important effect on the future path of carbon emissions are: the potential sizes of world oil and natural gas reserves; the cost and availability of carbon and non-carbon based backstop technologies; and the future behavior of OPEC. The last point is fairly important: Jorgenson and Wilcoxen (1992) have argued that the oil price shocks of the 1970's reduced U.S. energy demand enough to hold carbon dioxide emissions essentially constant from 1972 through 1985. Of course, from the point of view of the United States, an oil price increase is an undesirable means of lowering carbon emissions: the governments of OPEC countries capture all of the revenue; and oil prices are a costly instrument for attaining any particular emissions target.

Unlike many environmental problems, carbon emissions are a global externality. This would make implementing a carbon tax difficult for several reasons. First, the tax would have to be levied by individual governments, some of which might not be willing to participate. In particular, most OECD nations have now agreed that some sort of limit should be placed on carbon dioxide emissions. However, many less developed nations have been reluctant to adopt any carbon dioxide policy that might reduce their economic growth. Schelling (1992) has suggested that this poses an insurmountable obstacle to a unanimous international policy. Thus, a more likely outcome is that any global carbon dioxide policy would be incomplete: OECD nations would adopt the policy while developing nations would not.

A tax with only partial international coverage could be vitiated by movement of energy intensive industries away from participating countries to other nations. In fact, Hoel (1991) has shown that it is theoretically possible for such a policy to result in a net increase in world carbon dioxide emissions if nonparticipating nations have less efficient energy technologies. This is particularly likely to be a problem if the policy in question were an OECD tax and production was moving to less developed nations. To date, however, there has been only a modest amount research on how an incomplete carbon policy would affect patterns of international trade. A study was by Felder and Rutherford (1992), who refer to the redirected emissions as "leakage", find that they can be considerable. In Felder and Rutherford's model, CRTM, much of these new emissions arise because reductions in OECD oil demand would lower the world price of oil. This contrasts to the results of a studies by McKibbin and Wilcoxen (1992) and McKibbin and Wilcoxen (1995b) using the G-CUBED model that has a more complete specification of trade and capital flows than other studies of this question. They find that although there is some leakage due to substitution from the US to the rest of the world for a U.S. only tax and from the OECD to the rest of the world from an OECD wide carbon tax, this leakage is far too small to lead to a rise in global emissions even under the assumption of a substantially dirtier technology in the rest of the world.[10]

A second reason why the global nature of carbon dioxide emissions would make implementing a carbon tax difficult is that the point at which the tax is applied has important distributional effects. This point has been investigated by Whalley and Wigle (1990) who used a dynamic global general equilibrium model to assess the distributional effects of various carbon dioxide abatement policies. The central finding of their study was that carbon taxes could be applied in several different ways, each of which would achieve the same reduction in carbon emissions but with large differences in the distribution of costs. A carbon tax large enough to reduce emissions

[10] Detailed results from this model are presented in the latter part of the current paper.

substantially would raise an enormous amount of revenue. If the tax is applied at the point of production, it would be collected by the governments of producing countries. Were the tax to be applied to consumption, on the other hand, the revenue would flow to governments of consuming nations. Since the revenues are likely to be large, this is an important point.

The distributional implications of a carbon tax are also important within regions. As shown by Jorgenson and Wilcoxen (1991a), the principal effect of a carbon tax in the United States is to increase the price of coal. This comes about because coal is relatively cheap per unit of energy, and relatively high in carbon content, so a fixed dollar tax produces a much larger change in the price of coal than in the prices of oil or natural gas. The carbon tax needed to hold U.S. emissions constant would reduce coal use by about 25% from its base case value by the year 2020. Electric utilities, as the largest consumers of coal in the U.S., would see a rise in their costs of about 6% and would suffer a reduction in output of around 5%. Other sectors would be affected much less.

The concentration of costs in the coal sector has led some authors to suggest that a carbon tax is politically unlikely given the strength of the coal industry in the U.S. Congress. Two alternative taxes are sometimes proposed: a tax on the energy content of fossil fuels (a BTU tax) and an *ad valorem* tax[11] on fuel use. Like a carbon tax, both of the other taxes would operate by raising the cost of fuels and inducing fuel users to substitute away from fuel use.[12] Jorgenson and Wilcoxen (1991b) compared energy and *ad valorem* taxes to a carbon tax and found that

[11] An example of an *ad valorem* fuel tax that has often been proposed is an increased tax on gasoline.

[12] This reduction in energy use is often proposed as a goal for its own sake.

although carbon taxes have the largest effect on coal mining, they have the smallest overall effect on the economy as a whole. Energy taxes were fairly similar to carbon taxes but with slightly less impact on coal mining and slightly greater overall cost. In contrast, *ad valorem* taxes fell much more lightly on coal mining at the expense of having much greater effect on the rest of the economy through higher prices of oil.

Any tax large enough to achieve a significant reduction in carbon dioxide emissions will raise an enormous amount of revenue. Estimates range from tens to hundreds of billions of dollars per year. Precisely how this revenue is used will have a large effect of the overall economic cost of slowing global warming. In particular, if the revenue were used to reduce distortionary taxes elsewhere in the economy, or if it were used to lower government budget deficits, there would be large welfare gains which would offset some or all of the welfare losses associated with the carbon tax itself. This issue has been addressed by Shackleton, et al. (1992) and McKibbin and Wilcoxen (1994,1995a) who find that under an appropriate tax rebate scheme a unilateral carbon tax could actually raise U.S. gross national product.

A second distributional issue that has been raised is that carbon taxes have widely varying effects across households. The distributional impact of a carbon tax on the United States has been examined by Poterba (1991), DeWitt, Dowlatabadi and Kopp (1991), Jorgenson, Slesnick and Wilcoxen (1992), and by Schillo, et al. (1992). Poterba used a static, partial equilibrium approach to estimate the impact of a $100 per ton carbon tax on U.S. households having different levels of total expenditure. He concluded that the impact of a carbon tax would be slightly regressive by this measure, falling more heavily on households having low total expenditures. Classifying households by income rather than expenditure makes the tax appear slightly more regressive.

DeWitt, Dowlatabadi and Kopp conducted a similar study for a range of carbon taxes using a detailed econometric model of U.S. household energy consumption to estimate the response of energy consumption patterns to the tax. They find that there would be substantial differences in the economic impact across different geographic regions. Both Poterba and DeWitt, Dowlatabadi and Kopp point out that non-energy prices will also change, so that a general equilibrium approach is required to assess the full impact. This approach has been taken by Jorgenson, Slesnick and Wilcoxen who used a detailed, econometrically estimated intertemporal general equilibrium model to measure the lifetime incidence of a carbon tax on consumers in different demographic groups. They also find that the tax is mildly regressive, although the size of the effect varies across different consumer groups.

Finally, although most studies have focused on carbon taxes, Nordhaus (1989, 1991a) has assessed the following additional global warming policies using rough estimates of the costs and benefits of each: controlling CFCs, reforestation, and imposing a tax on gasoline. Comparing estimates of the marginal cost of reducing greenhouse emissions by the equivalent of one ton of carbon dioxide, Nordhaus argues that the optimal reduction in emissions of greenhouse gases could be achieved with a large reduction in CFCs and a comparatively small reduction in carbon dioxide emissions. Reforestation and gasoline taxes are found to be excessively expensive for the amount of carbon they remove from the atmosphere.

4 An Overview of The G-Cubed Model

In the next section we present some results from our Gcubed multi-country model to place empirical magnitudes on the issue of future emissions as well as the impacts of possible policy responses. To understand the results requires some understanding of the nature of the model underlying the analysis. Unfortunately it is not possible to give a detailed treatment of the model here but some key features are outlined.

The G-Cubed model is unique in the literature because of several reasons: it is based on econometric estimation of key relationships; it integrates the macroeconomic adjustment with the sectoral adjustment to changes in exogenous assumptions; and it captures the relationship between flows of goods and assets between economies as well as the links between changes in financial prices such as interest rates and exchange rates and the crucial role these financial prices play in the adjustment of the global economy to alternative projections and policies.

We first give a brief overview of the features of our model, G-Cubed, that are important for our analysis of the trade effects of environmental regulation. A more complete description is contained in McKibbin and Wilcoxen (1995a) or McKibbin and Wilcoxen (1994).

G-Cubed disaggregates the world economy into the eight economic regions listed in Table 2.

Table 2: List of Regions

United States
Japan
Australia
Other OECD (ROECD)
China
LDCs
Eastern Europe and the Former USSR (EEB)
Oil Exporting Developing Countries (OPEC)

We acknowledge that greater disaggregation of countries is desirable and we are currently undertaking this research. The particular disaggregation used in this paper reflects the current state of the model development and existing data limitations.

Each region is further decomposed into a household sector, a government sector, a financial sector, the twelve industries shown in Table 3, and a capital-goods producing sector.

Table 3: Industries in Each Region

1	Electric Utilities
2	Gas Utilities
3	Petroleum Refining
4	Coal Mining
5	Crude Oil and Gas Extraction
6	Other Mining
7	Agriculture, Fishing and Hunting
8	Forestry and Wood Products
9	Durable Manufacturing
10	Non-Durable Manufacturing
11	Transportation
12	Services

This disaggregation enables us to capture regional and sectoral differences in the impact of alternative environmental policies. In the remainder of this section we present an overview of the theoretical structure of the model. To keep notation as simple as possible we have not sub-scripted variables by country except where needed for clarity. The complete model, however, consists of eight of these submodels linked by international trade and asset flows.

Producer Behavior

Each producing sector is represented by a single firm which chooses it inputs and its level of investment in order to maximize its stock market value subject to a multiple-input production function and a vector of prices it takes to be exogenous. We assume that output can be represented by a constant elasticity of substitution (CES) function of inputs of capital (K), labor (L), energy (E) and materials (M). Omitting industry and country subscripts the production has the following form:

$$Q = A_O \left(\sum_{j=K,L,E,M} \delta_j^{1/\sigma_O} X_j^{(\sigma_O - 1)/\sigma_O} \right)^{\frac{\sigma_O}{(\sigma_O - 1)}}$$

where Q is the industry's output, X_j is the quantity of input j, and A_O, δ_j and σ_O are estimated parameters which vary across industries. In addition, the A_O and δ parameters vary across countries. Without loss of generality we constrain the δ's to sum to one.

Energy and materials, in turn, are CES aggregates of inputs of intermediate goods. The form of the function is the same as for the output tier but the inputs and estimated parameters are different. For energy:

$$X_E = A_E \left(\sum_{j=1}^{5} \delta_j^{1/\sigma_E} X_j^{(\sigma_E - 1)/\sigma_E} \right)^{\frac{\sigma_E}{(\sigma_E - 1)}}$$

where X_E is the industry's input of energy, X_j is the quantity of input j, and A_E, δ_j and σ_E are estimated parameters which vary across industries. As before, A_E and the δ parameters also vary across countries. The materials aggregation is defined in a similar manner.

In order to estimate the parameters in these equations we constructed a time-series data set on prices, industry outputs, value-added, and commodity inputs to industries for the United States. The following is a sketch of the approach we followed; complete details are contained in McKibbin and Wilcoxen (1995).

We began with the benchmark input-output transactions tables produced by the Bureau of Economic Analysis (BEA) for years 1958, 1963, 1967, 1972, 1977 and 1982.[13] The conventions used by the BEA have changed over time, so the raw tables are not completely comparable. We transformed the tables to make them consistent and aggregated them to twelve sectors. We then shifted consumer durables out of final consumption and into fixed investment.[14] We also increased the capital services element of final consumption to account for imputed service flows from durables and owner-occupied housing. Finally, we used a data set constructed by Dale Jorgenson and his colleagues to decompose the value added rows of the tables,[15] and a data set produced by the Office of Employment Projections at the Bureau of Labor Statistics to provide product prices. We use this data to estimate the elasticities of substitution in production at different levels of the nest.

To parameterize the other regions we impose the restriction that substitution elasticities are

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[13] A benchmark table also exists for 1947 but it has inadequate final demand detail for our purposes.

[14] The National Income and Product Accounts (and the benchmark input-output tables as well) treat purchases of consumer durables as consumption rather than investment.

[15] This data set is the work of several people over many years. In addition to Dale Jorgenson, some of the contributors were Lau Christiansen, Barbara Fraumeni, Mun Sing Ho and Dae Keun Park. The original source of data is the Fourteen Components of Income Tape produced by the Bureau of Economic Analysis. See Ho (1989) for more information.

equal throughout the world. In other words, we assume that each industry has the same energy, materials and KLEM substitution elasticities no matter where it is located. This is consistent with the econometric evidence of Kim and Lau in a number of papers (see for example Kim and Lau (1994)). However, the share parameters for other regions corresponding to individual countries (Japan, Australia, China, and approximately the Eastern Europe and Former Soviet Union region) are derived from input-output data for those regions and are not set equal to their U.S. counterparts. The share parameters for the remaining regions, which are aggregates of individual countries, are calculated by adjusting U.S. share parameters to account for actual final demand components from the aggregate national accounts data for each of the regions. In effect, we are assuming that all regions share production methods that differ in first-order properties but have identical second-order characteristics. This is intermediate between the extremes of assuming that the regions share common technologies and of allowing the technologies to differ across regions in arbitrary ways. Finally, the regions also differ in their endowments of primary factors and patterns of final demands. The main limitation of this approach is that there are very few benchmark input-output tables so our data set contains few observations. The problem is severe outside OECD countries.

Maximizing the firm's short run profit subject to its capital stock and the production functions above gives the firm's factor demand equations. At this point we add two further levels of detail: we assume that domestic and imported inputs of a given commodity are imperfect substitutes, and that imported products from different countries are imperfect substitutes for each other. Thus, the final decision the firm must make is the fraction of each of its inputs to buy from each region in the model (including the firm's home country). We represent this decision using a two-tier CES function, although in this version of the model data limitations have forced us to impose unitary substitution elasticities. We assume that all agents in the economy have identical preferences over foreign and domestic varieties of each particular commodity.[16] We parameterize this decision using trade shares based on aggregations of the 4-digit level of the United Nations SITC data for 1987. The result is a system of demand equations for domestic output and imports from each other region.

In addition to buying inputs and producing output, each sector must also choose its level of investment. We assume that capital is specific to each sector, that investment is subject to adjustment costs, and that firms choose their investment paths in order to maximize their market value. The capital stock changes by the amount of gross investment less depreciation of existing capital.

Following the cost of adjustment models of Lucas (1967), Treadway (1969) and Uzawa (1969) we assume that the investment process is subject to rising marginal costs of installation. To formalize this we adopt Uzawa's approach by assuming that in order to install J units of capital the firm must buy a larger quantity that is quadratic in the rate of investment.

Setting up and solving the firm's investment problem yields an equation for investment that depends on taxes, the size of the existing capital stock and marginal q (the ratio of the marginal value of a unit of capital to its purchase price).

Following Hayashi (1979), the investment function is modified to improve its empirical properties by writing investment as a linear function of this optimal investment and its current

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[16] Anything else would require time-series data on imports of products from each country of origin to each industry, which is not only unavailable but difficult to imagine collecting.

capital income. This improves the empirical behavior of the specification and is consistent with the existence of firms that are unable to borrow and therefore invest purely out of retained earnings.

In addition to the twelve industries discussed above, the model also includes a special sector that produces capital goods. This sector supplies the new investment goods demanded by other industries. Like other industries, the investment sector demands labor and capital services as well as intermediate inputs. We represent its behavior using a nested CES production function with the same structure as that used for the other sectors. However, we estimate the parameters of this function from price and quantity data for the final demand column for investment.

Households

Households consume goods and services in every period and also demand labor and capital services. Household capital services consist of the service flows of consumer durables plus residential housing. Households receive income by providing labor services to firms and the government, and from holding financial assets. In addition, they also may receive transfers from their region's government.

Within each region we assume household behavior can be modeled by a representative agent with an intertemporal utility function of the form:

$$U(t) = \int_t^{\infty} (\ln C(s) + \ln G(s)) e^{-\theta(s-t)} ds$$

where C(s) is the household's aggregate consumption of goods at time s, G(s) is government consumption, which we take to be a measure of public goods supply, and θ is the rate of time preference.[17] The household maximizes its utility subject to the constraint that the present value of consumption be equal to human wealth plus initial financial assets. Human wealth (H) is the present value of the future stream of after-tax labor income and transfer payments received by households. Financial wealth (F) is the sum of real money balances, real government bonds in the hands of the public (Barro neutrality does not hold in this model because some consumers are liquidity-constrained; more on this below), net holdings of claims against foreign residents and the value of capital in each sector. Under this specification, the value of each period's consumption is equal to the product of the time preference rate and household wealth.

Based on the evidence cited by Campbell and Mankiw (1987) and Hayashi (1982), however, we assume that only a portion of consumption is determined by these intertemporally-optimizing consumers and that the remainder is determined by after-tax current income. This can be interpreted as liquidity-constrained behavior or as permanent income behavior when household expectations are backward-looking. Either way we assume that total consumption is a weighted average of the forward looking consumption and backward-looking consumption.

Within each period the household allocates expenditure among goods and services in order to maximize C(s), its intratemporal utility index. In this version of the model we assume that C(s) may be represented by a Cobb-Douglas function of goods and services.[18]

The supply of household capital services is determined by consumers themselves who invest

[17] This specification imposes the restriction that household decisions on the allocations of expenditure among different goods at different points in time be separable.

[18] This specification has the undesirable effect of imposing unitary income and price elasticities. There is abundant empirical evidence against this assumption and we intend to relax it in future work.

in household capital in order to generate a desired flow of capital services. We assume that capital services are proportional to the household capital stock. As in the industry investment model, we assume that investment in household capital is subject to adjustment costs.

Government

We take each region's real government spending on goods and services to be exogenous and assume that it is allocated among final goods, services and labor in fixed proportions, which we set to 1987 values. Total government spending includes purchases of goods and services plus interest payments on government debt, investment tax credits and transfers to households. Government revenue comes from sales, corporate, and personal income taxes, and by issuing government debt. In addition, there can be taxes on externalities such as carbon dioxide emissions.

We assume that agents will not hold government bonds unless they expect the bonds to be serviced, and accordingly impose a transversality condition on the accumulation of public debt that has the effect of causing the stock of debt at each point in time to be equal to the present value of all future budget surpluses from that time forward. This condition alone, however, is insufficient to determine the time path of future surpluses: the government could pay off the debt by briefly raising taxes a lot; it could permanently raise taxes a small amount; or it could use some other policy. We assume that the government levies a lump sum tax equal to the value of interest payments on the outstanding debt. In effect, therefore, any increase in government debt is financed by consols, and future taxes are raised enough to accommodate the increased interest costs. Thus, any increase in the debt will be matched by an equal present value increase in future budget surpluses. Other fiscal closure rules are possible such as always returning to the original ratio of government debt to GDP. These closures have interesting implications but are beyond the scope of this paper (see Bryant and Long (1994)).

International Trade and Asset Flows

The eight regions in the model are linked by flows of goods and assets. Flows of goods are determined by the bilateral import demands described above. These demands are summarized in a set of bilateral trade matrices which give the flows of each good between exporting and importing countries. There is one 8 by 8 trade matrix for each of the twelve sectors for each country.

Trade imbalances are financed by flows of assets between countries. We assume asset markets are perfectly integrated across the OECD regions. With free mobility of capital, expected returns on loans denominated in the currencies of the various regions must be equalized period to period according to a set of interest arbitrage relations. In generating the baseline of the model we allow for risk premia on the assets of alternative currencies although in counterfactual simulations of the model, these risk premia are assumed to be constant and unaffected by the shocks we consider. For the non-OECD countries we also make the assumption that exchange rates are free to float at an annual frequency. We also assume that capital is freely mobile within the regions and between the regions and the rest of the world. This may appear to be overly simplified especially when many developing countries have restrictions on short term flows of financial capital. The capital flows in the model are the change in the current account and so are both flows of short term financial capital as well as direct foreign investment. In many countries with constraints on financial instruments there is nonetheless significant flows of direct foreign investment responding to changes in expected rates of return that we need to capture. Future work will focus more on modeling financial markets in the developing regions of the model. In addition, we assume that OPEC chooses its foreign lending in order to maintain a desired ratio of income to wealth subject to a fixed exchange rate with the U.S. dollar.

Labor Markets

We assume that labor is perfectly mobile among sectors within each region but is immobile between regions. Thus, within each region wages will be equal across sectors. The nominal wage is assumed to adjust slowly according to an overlapping contracts model where nominal wages are set based on current and expected inflation and on labor demand relative to labor supply. In the long run labor supply is given by the exogenous rate of population growth, but in the short run the hours worked can fluctuate depending on the demand for labor. For a given nominal wage, the demand for labor will determine short-run unemployment.

Money Markets

Finally, we assume that money enters the model via a constraint on transactions. We use a money demand function in which the demand for real money balances is a function of GDP and short-term nominal interest rates. The supply of money is determined by the balance sheet of the central bank and is exogenous.

5. Future Carbon Emissions and Consequences of Policy Responses

The G-Cubed model is used to project a range of variables. This is not as straightforward as in conventional models because of the role of expectations about future events that is central to the G-Cubed model. The future paths of exogenous variables including government policy instruments need to be specified for a long period into the future because agents in the model react to these future policies in the earlier periods.

The most important of the exogenous variables that we project outside the model are shown in Table 4. Our key assumptions are set out in Table 5.

Given these assumptions, we solve for the model's perfect-foresight equilibrium growth path over the period 1990-2050 using software developed by McKibbin (1994) for solving large models with rational expectations on a personal computer. For the purposes of this paper, the most important results of the base case calculation are the future paths of carbon dioxide emissions, which are shown in Figure 1. Global emissions rise from 5,388 million metric tons of carbon in 1990 to 11,752 million tons in 2020. The change in carbon emissions in individual countries and regions between 1990 and 2020 (in million of metric tons) are: United States (1,339 to 1,854); Japan (316 to 505); Australia (76 to166); Rest of the OECD (1,025 to 1,980); China (608 to 1,914); and other non oil developing countries (1,015 to 2,315). Emissions growth in China and the other developing country region is particularly high because economic growth is projected to be highest in those regions.

Regional shares in total emissions and their projected evolution are shown in Table 6. These results are preliminary and should be interpreted cautiously. In future work with Philip Bagnoli we expect to test the sensitivity of these figures to assumptions about the projected paths of productivity, population and energy efficiency improvements.

Table 4: Key Exogenous Variables

- population growth by region;
- productivity growth by sector by region;
- energy efficiency improvements by sector by region;
- tax rates by region;
- fiscal spending patterns on each sector's output by region;
- monetary policy by region
- real price of oil;
- other exogenous shifts in spending patterns..

Table 5: Regional Assumptions Used in Generating the Baseline

	USA	Japan	Aust	ROECD	China	LDCs	EEB
Population growth	0.5%	0.0%	0.8%	0.7%	1.5%	1.0%	0.5%
non-energy productivity growth	2.0%	2.5%	2.2%	2.3%	4%	2.5%	2.0%
energy sector productivity growth	1.5%	2.0%	1.7%	1.8%	4%	2.5%	1.5%
energy efficiency growth	1%	1%	1%	1%	1%	1%	1%
tax rates	1990 levels	1990 levels	1990 levels	1990 levels	1990 levels	1990 levels	1990 levels
fiscal spending	1990 shares	1990 shares	1990 shares	1990 shares	1990 shares	1990 shares	1990 shares
monetary policy (fixed money growth rate)	2.9 %	1.25 %	1.64 %	3.98 %	12.84 %	6.48 %	23.81 %
real oil price	1990 levels	1990 levels	1990 levels	1990 levels	1990 levels	1990 levels	1990 levels

Table 6: Share of Each Region in Global Carbon Emissions

	1990	2000	2010	2020
USA	24.9	21.1	16.7	12.7
Japan	5.9	5.1	4.2	3.5
Australia	1.4	1.4	1.3	1.1
Other OECD	19.0	17.4	15.5	13.6
China	11.3	14.5	15	16.2
LDCs	18.8	19.1	21.9	23.9
Eastern Europe and former Soviet Union (EEB)	18.7	21.4	25.5	29.0

These results show that the share of emissions from China and other developing countries (including many countries in the Asia Pacific region) is projected to rise over the next 30 years. The share of carbon emissions from already industrialized economies within the OECD is projected to fall although absolute emission from these economies are expected to rise.

Next we calculate the size of carbon taxes necessary to stabilize emissions in each region by the year 2000 at the level of 1990, given that the revenue is used to reduce fiscal deficits in each country by the amount of revenue raised by that country. Several important assumptions need to be highlighted relative to other studies of this issue and relative to previous studies undertaken using the G-Cubed model. First, we begin the simulation in 1990, but since 1990 has actually passed, we phase the carbon tax in gradually starting in 1995. In other words, the simulations are conducted as though the tax were announced in 1990 to start in 1995. (As a result, asset prices adjust somewhat before 1995.) The tax is set so that emissions gradually fall to the 1990 target by the year 2000 rather than stabilizing emissions from 1995 at the 1990 level. We assume that after the year 2000 the tax rate is held constant; this will mean that emissions will rise after the year 2000. Finally, it is important to stress that the results presented here are for a tax on the emissions, rather than production, of carbon. Under an emissions-based tax, imports of fossil fuels are subject to the tax but exports are not. In contrast, under a production-based tax, exports would be taxed but imports would not be.[19]

Table 7: Emission Stabilization Taxes by the year 2000

	US Only	OECD wide	Global
	US$/t carbon (1990 dollars)	US$/t carbon (1990 dollars)	US$/t carbon (1990 dollars)
United States	15.60	16.80	19.20
Japan		55.20	57.60
Australia		28.80	28.80
Other OECD		48.00	48.60
China			9.60
Developing Countries			9.00
Eastern Europe and Former Soviet Union			25.20

Table 7 contains the size of the tax required to be in place by the year 2000 so that emission

[19] This is a departure from other studies and also our own previous work in which the tax applied to imports and all domestic production (and hence exports). The distinction is unimportant for the United States because fuel exports account for a very small share of total production. It is, however, very important for regions like OPEC or Australia where much of domestic fuel production is exported. This is explored further in McKibbin, Pearce and Stoeckel (1994).

in the year 2000 are at 1990 level. Three cases are considered. The first is when the United States acts alone; the second with the entire OECD acting and the third when there is a global carbon tax levied. Take the example of the United States. The tax required in the United States to achieve 1990 emissions in the year 2000, when only the United States levies the tax, starts at $2.60 per metric ton in 1995 and then rises uniformly to reach $15.60 per ton by the year 2000. The size and rate of growth of the tax depends strongly on the assumption that the revenue is used to reduce the fiscal deficit. It also depends on our assumptions about the growth of sectoral productivity and energy efficiency improvements.

The results in Table 7 of the differntial taxes required for stabilization may seem counter intuitive, especially the result that Japan needs a relatively high tax. This result reflects a number of factors. Firstly, the price of energy is much higher in Japan that in the United States when expressed in $US. Thus a dollar per ton of carbon in Japan is a smaller percent of the underlying price of carbon than it is in the United States. Secondly, Japan is relatively efficient in energy use and therefore additional reductions in energy use require a proportionately larger tax than say for the United States which is relatively inefficient in energy use. Taking these two factors into account, it is much clearer why Japan would need a higher dollar tax per unit of carbon that the United States. It also illustrates why a modelling framework is useful in accounting for factors that a rule of thumb approach may ignore.

Emissions are gradually reduced to 1990 levels by the year 2000, but begin rising after that because the tax is held constant. This is an important aspect of the problem of taxing carbon emissions. Because the future path of emissions is projected to rise continually in the business as usual scenario, targeting emissions at 1990 levels after the year 2000 will require a continually rising tax. In the experiments report here we assume that the tax is held constant after the year 2000 so emissions continue to rise after 2000 but from a lower level.

It can also be seen in Table 7 that as more countries participate in the carbon stabilization agreement, higher taxes are needed for the United States. This primarily occurs because a unilateral U.S. tax causes a larger drop in U.S. GDP, which reduces energy demand and lowers carbon emissions. When more countries tax carbon emissions, the effect on U.S. GDP is smaller and a higher tax is needed to achieve the same reduction in U.S. emissions.

Figure 2 shows the percentage reduction in global emissions as a result of each of the carbon taxes.[20] The U.S. acting alone has a relatively small impact on global emissions. Substitution away from U.S. goods offsets the direct effect of the tax slightly, but a U.S. carbon tax does indeed lower global emissions. When all of the OECD economies simultaneously reduce emissions, the impact is still far from stabilizing global emissions. This is because non-OECD economies account for a large portion of the increase in carbon emissions between 1990 and 2020. Finally, by construction, the global tax reduces year 2000 global emissions to 1990 levels. The percentage reduction is also relatively constant by 2020 even though the level of emissions is rising after 2000.

In Table 8 we present the effects on GDP in each region of the carbon taxes aimed at stabilization of emissions. These taxes are implemented gradually so the output loss fall gradually over time. The peak loss occurs in 2000 after which the GDP losses are reduced as resources are gradually reallocated throughout the economies. Rather than present a year by year

[20] For reference, G-Cubed's baseline global emissions in 2020 are around 48% above the level of 1990.

comparison we select three representative years.

An important aspect of Table 8 is that the GDP loss varies considerably across countries even though the simulated target is for all countries to keep emissions at 1990 levels by the year 2000. The reasons for the differential effects on countries are varied. Regions such as China and other developing countries have high expected future growth because of their stages of development and thus the requirement to stabilize emissions will impose a higher burden on these regions relative to advanced industrialized economies. Even Australia bears a high burden because it has the highest projected population growth in the OECD economies. Difference are also due to differences in the energy share of production and the share of fossil fuels in energy production. Australia and China

stand out because coal is an important factor in the generation of energy. The tax does induce a substitution away from coal to less carbon intensive energy sources but this shift involved a significant

Table 8: GDP Loss relative to Baseline from Stabilizing Emissions in 2000
(percentage deviation from baseline)

	2000	2010	2020
USA	-0.08	0.01	0.02
Japan	-0.45	-0.25	-0.23
Australia	-0.75	-0.62	-0.60
Other OECD	-0.56	-0.33	-0.30
China	-1.34	-0.52	-0.39
LDCs	-0.38	-0.17	-0.12

adjustment cost that is illustrated by the GDP loss. A further difference is caused by the reliance on carbon intensive production (either in terms of coal directly or coal embodied in other goods) for income generation through exports.

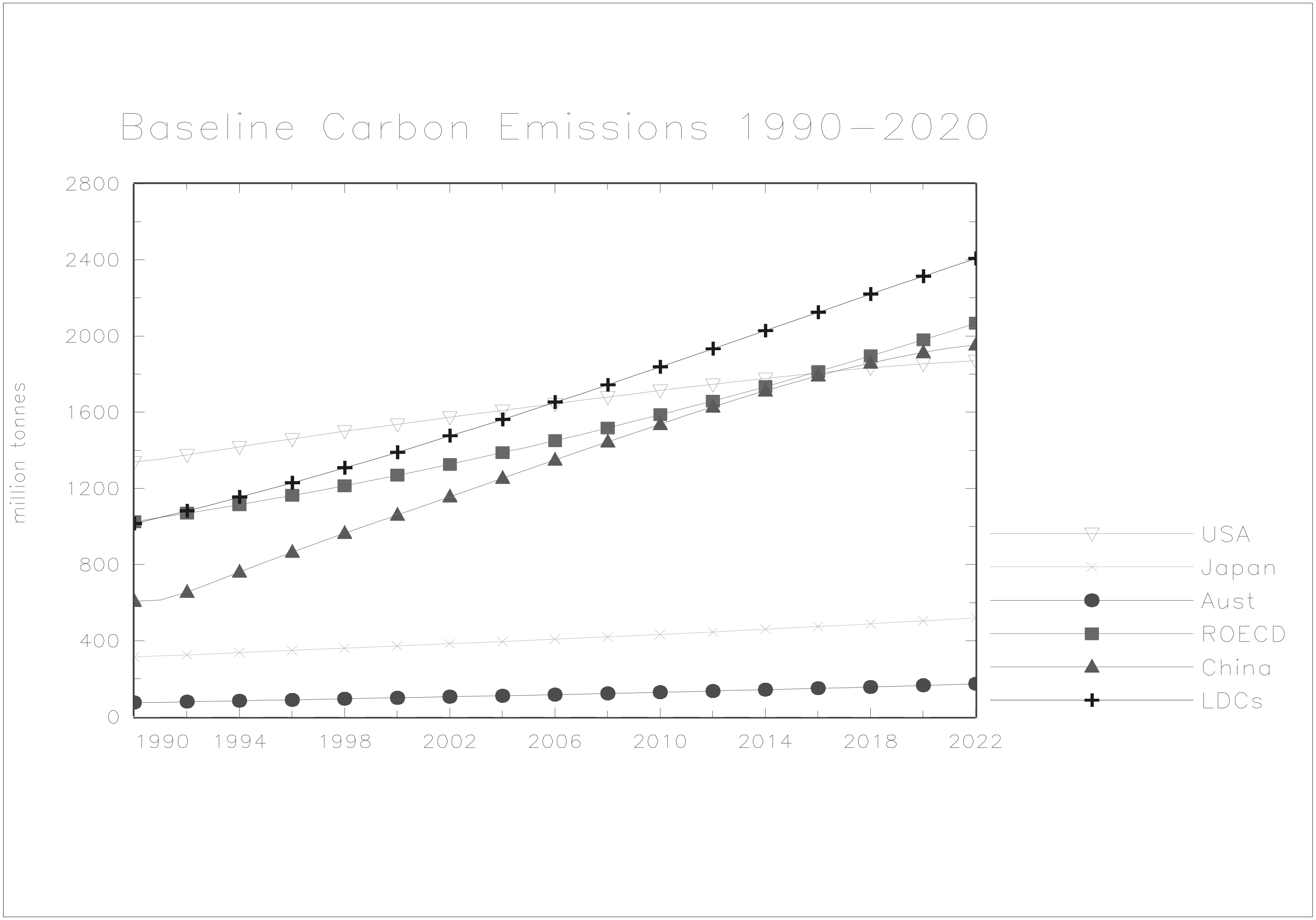
6 Conclusion

There are still many unresolved issues in the debate on the policies that should be implemented to mitigate the emission of greenhouse gases. Apart from great scientific uncertainty about the scale of the greenhouse problem there is also considerable uncertainty about the economic costs and benefits of implementing policies to reduce greenhouse gas emissions.

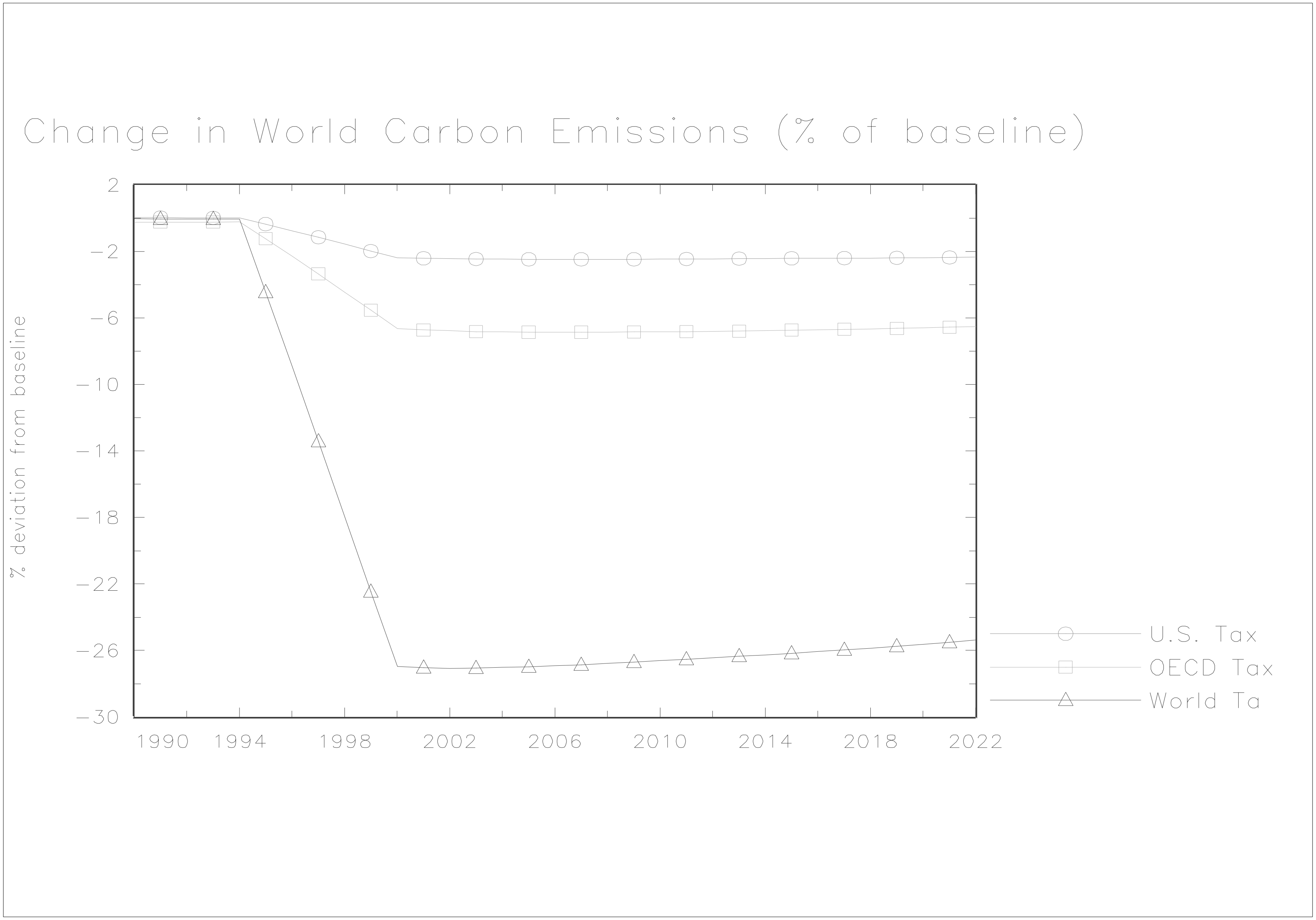
The most important greenhouse gas is carbon dioxide emissions and this was the focus of our paper. It is likely that some form of carbon tax or a tradeable emission permit system aimed at distributing a fixed target for world emissions to those countries that can reduce emissions at least cost will be the most effective way to reduce emission of carbon dioxide at least cost. Yet the economic costs are likely to be large and very different across countries and regions. The issue of burden sharing is fundamental to any political resolution if indeed a policy response is deemed necessary. The countries that stand to lose most out of a coordinated strategy that does not include side payments are likely to be the those countries with large potential growth rates either because of the stage of economic development or because of high potential population growth. Countries with a heavy reliance on fossil fuels for energy generation are also likely to suffer relatively more.

In this paper we have shown that there is considerable insight to be gained from attempting to model the impacts of greenhouse mitigation strategies as well as using economic analysis to undertake projections of possible trends in the world economy over the next 30 years. Given the existing scientific and economic uncertainties as well as the recent outcome of the Conference of the Parties meeting in Berlin, the challenge is to undertake more research on the magnitude and distribution of the cost of greenhouse gas mitigation strategies before inventing any more unsustainable global agreements.

(B-1): Baseline Carbon Emissions



(B-2): Change in World Carbon Emissions as a Results of Carbon Tax Targetted at 1990 Emissions by the year 2000



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