'Hot and Bothered' in the Greenhouse: The Economics of Global Warming and International Finance

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ACRONYMS

ATP	ability-to-pay
CBA	cost-benefit analysis
CFC	chlorofluorocarbon
CO_2	carbon dioxide
CH_4	methane
CSERGE	Centre for Social and Economic Research on the Global Environment
DICE	dynamic integrated model of climate and the economy
ECU	Environmental Change Unit
EIB	European Investment Bank
EPA	Environmental Protection Agency
EU	European Union
FCCC	Framework Convention on Climate Change
FUND	framework for uncertainty, negotiation and distribution
GCM	global climate model
GHG	greenhouse gas
GREEN	general equilibrium environmental
Gt	giga tonnes
IFI	international financial institution
IPPC	Inter-Governmental Panel on Climate Change
MAC	marginal abatement cost
MEC	marginal environmental cost
MERGE	model for evaluating the regional and global effects
MNPB	marginal net private benefit
MO	Meteorological Office
N_2O	nitrous oxide
OECD	Organisation for Economic Cooperation and Development
O3	ozone
ROR	rate of return
SF6	sulphurhexafluoride
SRTP	social rate of time preference
UCL	University College London
UEA	University of East Anglia
UN	United Nations
WTP	willingness-to-pay

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SUMMARY AND CONCLUSIONS

The primary objective of this paper is to provide an accessible review of the role that economics is playing to clarify the main issues associated with the debate on global warming. From this, it also sketches an outline policy agenda for international financial institutions, such as the EIB.

Global warming is at or near the top of most environment agendas and at the heart of the debate on sustainable development (1). This is not surprising. There is now a consensus among the international scientific community that humankind is exerting a discernible influence on climate by actions that result in an accumulation of greenhouse gases (GHG) in the atmosphere. Global climate is changing – it is generally becoming warmer and wetter – at a faster rate than at any time since the last major ice age, 12,000 years ago. In this context, the key questions pertain to whether and to what extent GHG emissions should be controlled, how and at whose expense.

The economics profession possesses concepts and techniques and has considerable experience of their applications – developed in a variety of fields, such as public goods, externalities, cost benefit analysis (CBA), equity, uncertainty, environmental management and game theory – that can inform the policy debate on the greenhouse effect. The paper presents the theory and associated empirical evidence from a review of a large body of the relevant literature.

Commonly held notions of the meaning of sustainable development suggest that because the atmosphere is critical to current life on earth, it should be managed with extreme care. If this is close to stating the obvious, public economics adds theoretical weight to the argument. It explains why a problem such as over-exploitation of the atmosphere is likely to arise. The atmosphere has some of the characteristics of a public good, relatively unfettered access to which gives rise to a classic example of an externality. Some form of intervention is needed to ensure that the atmosphere is exploited in the public interest in a sustainable way.

For more concrete evidence to support the case for GHG abatement and adaptation to climate change, it is necessary to turn to the findings of CBA. Global warming is an area in which the economic theory and practice of CBA are being tested to their limits. The impressive volume and quality of analysis carried out so far suggests, however, that the difference between the aggregate benefits of abatement and the aggregate costs of mitigation may not be significant.

The case for action is better made with reference to concerns for intra- and inter-generational equity. Poor developing countries are predicted to bear a disproportionate share of the future costs of global warming largely caused by the past behaviour of rich developed countries. When this consideration is taken into account, the estimates of damage cost rise by a significant margin. Moreover, future generations have as much claim as the present to the earth's life support systems, such as those provided by a stable atmosphere. This argues for applying a modest discount rate, which increases the estimates of the benefits of abatement relative to the costs. Finally, aversion to risk, especially of possible catastrophic events, in the face of enormous uncertainty, reinforces the case for a degree of precautionary action now. In this regard, there is a large premium on greater knowledge and improvements in understanding of the subject.

Economic theory and empirical evidence justify the faith that the international community appears to place in tradable quotas as the best international policy instrument. By the yardstick of cost effectiveness, the greater the opportunities for trade in quotas the better. The 'flexibility mechanisms' of the Kyoto Protocol offer a number of options to develop.

International co-operation in the field of global warming should yield positive benefits. But it is necessary to devise enforcement arrangements and incentives to overcome free-rider problems and to promote greater developing country participation.

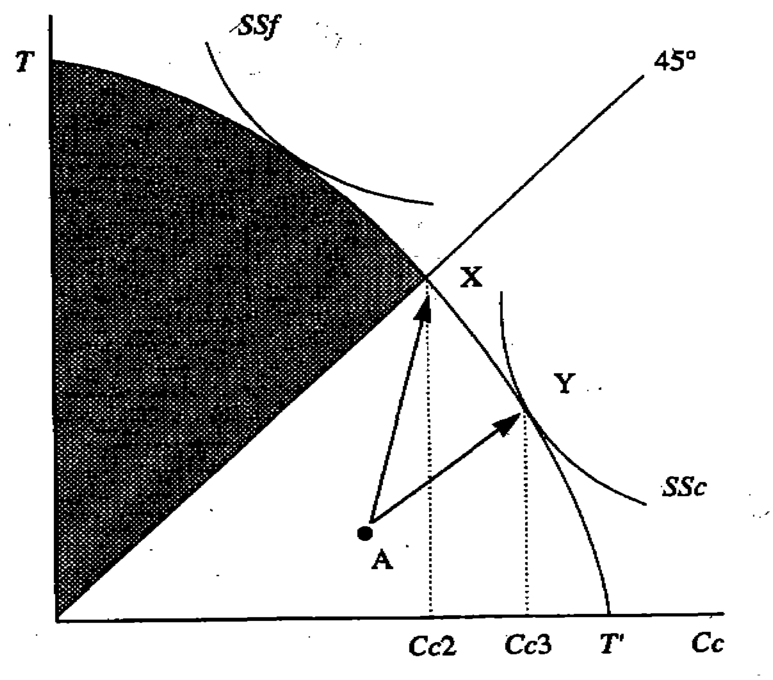
The general conclusion is that each international financial institution, according to its respective mandate and for reasons of self-interest, should develop a comprehensive policy to address the issues of global warming in support of international efforts taken so far. The paper identifies four possible ingredients of a policy package.

1. INTRODUCTION: GLOBAL WARMING AND SUSTAINABLE DEVELOPMENT (2)

Concern about global warming is at the centre of the debate on sustainable development. This and the following section briefly explain why. Most economists agree on a broad definition of the aims of sustainable development. These are to increase average human wellbeing today, without a worsening of either the distribution of wellbeing today or the wellbeing of future generations. Sustainable development thus has a tripartite goal of an enduring increase in per capita wellbeing, coupled with reductions in poverty, without depleting the resource base on which human advancement is founded. It shares the inter-generational time horizon of the global warming debate.

These relationships are illustrated in a highly simplified manner in Figure 1.

Figure 1: Optimal and Sustainable Consumption over Time



Source: Atkinson et al. (1997)

Concern for the wellbeing of future generations suggests the need to use a relatively low discount rate and possibly to make sacrifices today for the benefit of those living tomorrow. T^1T describes how consumption can be allocated between consumption today and consumption tomorrow. SSc and SSf are inter-temporal welfare functions, where SSc is relatively biased towards the preferences of the present and SSf to those of future generations. Strict sustainable development between generations occurs along the 45° line. Starting at, say, point A, economic efficiency requires that society move to the production possibility frontier T^1T. Sustainable development requires the point be X rather than Y. X and Y both yield an increase in consumption for the present as well as the future generations. With Y as the start point, however, sustainable development at X would require the present generation to sacrifice consumption. At X, the discount rate – the absolute value of the slope of T^1T – is lower than at Y.

In order that future generations have the same welfare-generating potential as the present generation, the present generation must bequeath an equivalent, population-adjusted, capital stock, as that which it has inherited. The capital stock is made up of several parts. A distinction can be made between renewable (human-made and some natural, respectively Km and Kn) and non-renewable (other natural, Kn*) capital. There are also the stock of human knowledge and skills (Kh) and social capital (culture, institutions, etc., Ks). Therefore the total capital stock (K) can be defined as:

$$K = Km + Kh + Ks + Kn + Kn^*$$

A crucial issue for sustainable development is the extent to which one component of capital can be substituted for another over time. According to the 'weak' definition of sustainability, complete substitution is possible. This is in line with the growth models of the 1970s (see, for example, Solow (1974)), which assumed that the marginal product of non-renewable natural capital tends to infinity as its stock approaches zero. Two other rules must be satisfied: first, the rents from the exploitation of natural capital should be reinvested in human-made capital; and, second, natural capital should be depleted to the point where the proceeds from exploitation earn the same return as any alternative form of capital (Hartwick and Olewiler 1998). To permit a comparison between different components of capital, where value is determined by a future stream of returns, it is necessary to use a common yardstick like money.

Although economists have made considerable progress in the theory of environmental valuation, for various reasons, the application is patchy and, in practice, it is usually difficult to make a robust rate of return comparison between investment in natural and human-made capital. Due to the nature of natural capital and the benefits it bestows, there is a possibility that natural resources will be under-valued and over-exploited. Of even more concern, some natural assets may be irreplaceable. They may fulfil certain life-support functions for which there is no substitute and such critical capital should be passed on to future generations in full. This is the basis for the 'strong' sustainability argument, according to which, total capital should still be kept constant but subject to the extra constraint that the stock of 'critical' natural capital should be maintained. It can be debated which capital is critical in this sense. The basic biogeochemical cycles – nutrient, carbon and water – would seem to be strong candidates. The Annex explains how the atmosphere regulates the climate upon which human life on earth depends.

The critical role of the atmosphere is recognised in the 'Framework Convention on Climate Change' (FCCC) (UN 1992), the objective of which is '.... to achieve .... stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system .... to enable economic development to proceed in a sustainable manner' (Article 2). The argument for a custodian approach to environmental assets like the earth's atmosphere is reinforced by a lack of understanding of the processes at work, the possibility of thresholds at which ecosystems might collapse and the difficulty, if not impossibility, of repairing the asset once it has been degraded.

2. A GLOBAL COMMONS

Issues such as global warming are of no surprise to economists. The atmosphere has public good characteristics in the sense that it is difficult to exclude any one consumer from using its life-support and other services. But it is now realised that the atmosphere can be depleted. Excessive use of the atmosphere today will deprive consumers of its services tomorrow. Failure on the part of an individual to recognise that her consumption imposes costs on others through climate change is a classic example of an externality. In the standard reference to the theory, Baumol and Oates (1988) establishes two conditions for the existence of an environmental externality, which can be paraphrased as follows:

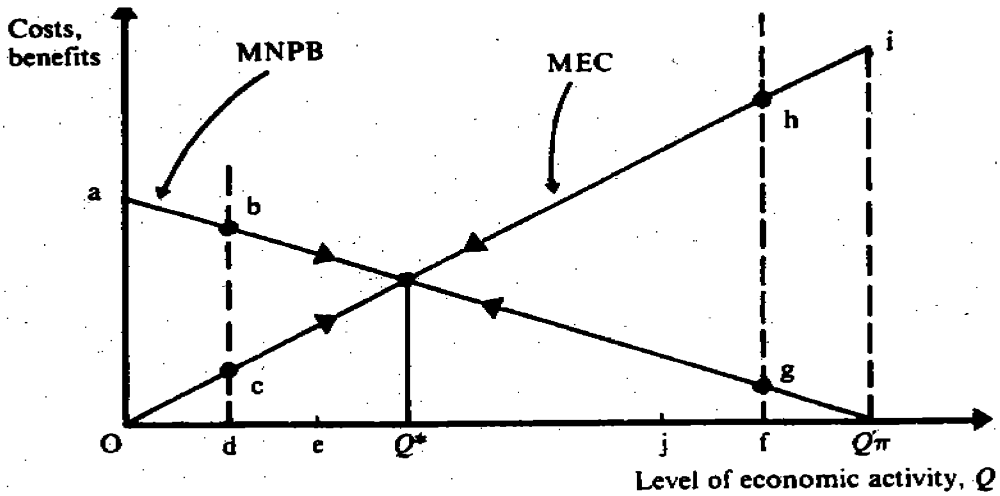
> Condition 1: An externality is present whenever the utility or production relationships of one individual (A) include variables whose value is chosen by another individual (B) without particular attention to the effects on A.
>
> Condition 2: B does not pay (or receive compensation) for her activity equal in value to the resulting costs (or benefits) to A.

The literature on 'rights' distinguishes three principal regimes, individual, common and open access (Bromley 1991). The atmosphere is governed by the latter and, as pointed out in the seminal though famously, wrongly titled paper, 'Tragedy of the Commons' (Hardin 1968), there is no market to prevent over-exploitation of such resources.

The issue can be explored further using the standard algebraic and geometric tools of neo-classical economics (Pearce and Turner 1990; Varian 1996).

In Figure 2, the level of activity (environmental damage) of the polluter is shown on the horizontal axis. MNPB (marginal net private benefit) is the difference between private revenues and private costs. MEC (marginal external cost) is the value of the damage done by pollution to other agents.

Figure 2: The Effect of an External Cost on the Optimal Level of Economic Activity



Source: Pearce and Turner (1990)

Ignoring the effect of the externality, the polluter's optimal level of activity is QΠ (MNPB = 0); taking the externality into account, the optimal activity level (and pollution) falls to Q*, at which MNPB = MEC. According to a theorem first propounded by Ronald Coase (1960), markets can be coaxed in the direction of the optimal amount of the externality by assigning property rights, regardless of who holds the rights (3). The 'Coase Theorem' is now, however, treated as little more than an intellectual diversion since it is hard to conceive of real-world examples of the bargaining process it entails, not least because of high transaction costs. Thus an alternative form of intervention is necessary to manage open access resources, such as the atmosphere, in an efficient way. This is the subject of sections 6 and 7.

3. THE ECONOMIC COSTS AND BENEFITS OF GLOBAL WARMING

By exploring the economic costs and benefits of abatement and adaptation, applied economics can throw light on the questions whether and to what extent GHG emissions should be controlled. But the process of CBA may be more important than the results in view of the nature of global warming. Among the reasons for the difficulties experienced in the application of CBA to global warming are the tortuous causal chain of non-linear linkages, the long atmospheric lifetime of GHGs and the likely large differentiation of effects by time and location (IPPCc 1996). There is also considerable uncertainty about baseline rates of emission, the costs of emission reduction and adaptation, the benefits of abatement, the effectiveness of alternative policy options and, as seen below, the correct rate of discount.

Leaving issues of equity until Section 4, the CBA of global warming can be divided into four parts: damage costs (4), abatement and adaptation costs, integrated assessment models and the treatment of uncertainty.

CBA aims to secure potential 'Pareto' efficiency (5). Broadly there are two options to moderate the impacts of global warming. The first is to limit the net amount of GHG emissions through abatement and sequestration. The second is to ease the impacts through protection and adaptation. Analytically, the optimal combination of the two options can be found by minimising total cost, defined as the costs of abatement (or sequestration) plus the costs of adaptation plus the costs of any residual damage after adaptation. The following representation is taken from Fankhauser (1995):

$$\text{Min}_{(m,e)} \quad C1(e) + C2(m) + C3(T,m)$$

subject to $T = f(e)$

where

C = costs

e = the level of abatement

m = the degree of adaptation

T = the temperature change

The standard CBA result for optimisation requires that two conditions hold:

> Condition 1: The marginal costs of abatement equal the additional benefits from warming avoided.
>
> Condition 2: The marginal costs of adaptation equal the additional benefits from mitigated damages.

Since e and m are interdependent – for example, if the consequences of global warming can be easily accommodated by adaptation, there may be less need for preventive measures – ideally they should be chosen simultaneously. But the way this is dealt with in the literature, as well as in practice, decision-making is sequential. Abatement is optimised at the global level and each geographical region is left to face its own issues of adaptation, such as appropriate responses to sea level change. Fankhauser shows that a two-step approach, in which the region is a climate taker, is equivalent to simultaneous optimisation, provided that the global warming damage function takes a particular form.

Most CBA studies of global warming acknowledge such complexities without necessarily reflecting them in the total damage costs (which may be overstated) or the total abatement costs (which may be understated). This may, for instance, explain the very wide range of cost estimates for sea level rise in the USA; ideally these should combine the costs of adaptation with any residual damage costs. With this additional health warning, the paper now turns to the empirical evidence on global warming.

There is a huge and rapidly growing literature dedicated to measuring and valuing the potential damage of global warming. Much of this deals with impacts in individual sectors and fields (for instance, agriculture (see European Commission 1997), health (see Parry and Haines 1994) and bio-diversity), applying the full panoply of conventional, implicit and constructed market-based valuation techniques (for instance, production function, property values and contingent valuation, respectively). Pearce (1993) provides a good introduction to economic valuation techniques and Fankhauser (1995) and the IPPC (IPPCc 1996) review the damage function estimates by sector.

This paper, however, is limited to a review of global and world regional damage estimates. Most of these are concerned with a doubling of the pre-industrial carbon dioxide-equivalent atmospheric concentration of all GHGs, referred to as the '2 x CO_2' benchmark. The estimates should be treated with extreme caution. Primary estimates are predominantly for the USA and other OECD countries (see, by contrast, Hulme *et al.* on Africa (1995)) and relate to present-day economic structures. Table 1 summarises the main findings from five studies for the USA (Cline, Fankhauser, Nordhaus, Titus and Tol) and the more comprehensive estimates by world region by Fankhauser (1995) and Tol (1996). For the OECD, all the estimates fall within a narrow range of 1–2.5 per cent of 1990 GDP though this should not be interpreted as evidence of robustness since the underlying sources are largely the same. More noteworthy is that the damage figures are orders of magnitude greater for developing than developed countries, mainly due to higher adverse impacts on health and natural habitats.

The benchmark doubling could occur around the middle of the next century but fossil fuel reserves are probably sufficient for atmospheric concentrations to rise to six-fold pre-industrial levels. Taking a 300-year time horizon, Cline (1992) estimates a loss of USA GDP of 6 per cent associated with warming of 10°C. However, the figure is only illustrative. A scenario such as this would take the world into the realm of climate 'catastrophes'.

Studies of mitigation measures estimate the economic costs of stabilisation of CO_2 in the atmosphere - often at the level of 1990 - against a baseline, 'business-as-usual' emission scenario. They take into account options that eliminate GHG emissions (sources) as well as options that offset emissions (sinks).

Table 1: Estimates of the Economic Costs of Global Warming

1.1: 2 X CO_2 Annual Damage to 1990 US Economy (US$ billion)

Selected damage category (where assessed)	*Cline*	*Fankhauser*	*Nordhaus*	*Titus*	*Tol*
Agriculture	17.5	8.4	1.1	1.2	10.0
Forest loss	3.3	0.7	Small	43.6	-
Sea level rise	7.0	9.0	12.2	5.7	8.5
Electricity	11.2	7.9	1.1	5.6	-
Human amenity	-	-		-	12.0
Human life	5.8	11.4	-	9.4	37.4
Water availability	7.0	15.6	-	11.4	-
Air pollution	3.5	7.3	-	27.2	-
Total	61.1	69.5	55.5	139.2	74.2
% of GDP	1.1	1.3	1.0	2.5	1.5

Source: IPPCc (1996)

1.2: 2 X CO_2 Annual Damage by Region (% GDP)

Region	*Fankhauser*	*Tol*
EU	1.4	
US	1.3	
Total OECD	1.3	1.6
Eastern Europe/former USSR	0.7	-0.3
S and SE Asia	-	8.6
Africa	-	8.7
Middle East	-	4.1
Total non-OECD	1.6	2.7
Total World	1.4	1.9

Source: Fankhauser (1995) and Tol (1996)

The 'Kaya Identity' helps to understand the main driving forces:

$$CO_2 \quad = \quad CO_2/E \quad x \quad E/Q \quad x \quad Q/L \quad x \quad L$$

where

E = unit energy

Q = unit output

L = population

It suggests that the costs of a specific stabilisation target will be sensitive to demographic factors and economic growth and, in the energy sector, to both demand-side (improved efficiency) and supply-side (reduced fossil fuel dependency) factors.

The cost models are of two broad types. 'Bottom-up' models are based on engineering studies of alternative technologies. 'Top-down' models are based on an economic approach. In the case of general equilibrium models, they are driven by a carbon tax-induced change in relative prices. There is considerable variation in the findings.

For instance, Table 2 shows that the estimates of GDP loss due to stabilisation of GHG emissions at 1990 levels for the USA from three 'top-down' models (Edmonds Reilly, GREEN and Manne Richels) lie in the range 0.8–2.1 per cent GDP in year 2050. The costs are higher for developing countries. 'Bottom-up' models are more optimistic and predict relatively low abatement costs even for substantial emission cuts._They draw attention to 'no regrets' measures, which can be achieved at low or zero extra costs (Grubb *et al.* 1994), the secondary benefits referred to above and the opportunity of a 'double dividend' from tax recycling, with taxes on environmental 'bads' replacing taxes on economic goods (Pearce 1991). Fankhauser (1995) suggests that the true costs of abatement lie somewhere in between the two model estimates.

Table 2: Estimates of the Economic Costs of the Stabilisation of GHG Emissions

GDP Loss as a Percentage of the Baseline in 2050, Emission Stabilisation at 1990 Levels

	Edmonds Reilly	GREEN	Manne Richels
USA	0.81	0.36	2.11
other OECD	0.92	0.62	1.31
ex-USSR	0.33	2.07	0.79
China	5.67	5.56	4.05
Rest of World	2.96	4.45	5.38

Source: Fankhauser (1995), source OECD

'Bottom-up' models tend to over-estimate the scope for cheap technology fixes, especially in the field of renewable energy, whereas the energy market cannot be made to work as efficiently as assumed in the economic models.

So far the paper has reviewed the literature on the economic costs of '2 X CO_2' and of stabilising GHG emissions at 1990 levels, which would lead to an approximate doubling in pre-industrial concentrations of GHG in 2100 instead of 2050 under business-as-usual. Inspite of all the brouhaha on global warming, the findings suggest that the difference between the aggregate benefits of mitigated damage and the aggregate costs of abatement may not be significant.

Further insight into the question of the optimal degree of control and associated policy measures is provided by the integrated assessment models (IAMs), which describe the interplay between human activities, ecosystems and the atmosphere-ocean system. One of the best known is the 'Dynamic Integrated Model of Climate and the Economy' (DICE), associated with Nordhaus (1994). Typical of the genre, DICE uses a neo-classical growth model. It incorporates the costs and benefits of carbon abatement to define an optimal, welfare-maximising growth path of the economy along which marginal abatements costs equal marginal damage (Nordhaus 1991). The deterministic version of the model yields modest GHG control rates of 10–13 per cent of base case emissions in the period 2005–75. It results in an increase in the discounted present value of consumption of about US $ 270 billion or about 0.04 per cent of discounted baseline consumption. According to this approach, control should start now, albeit to a modest extent, and continue for a long time.

The other well-known models – FUND (Tol 1996) and MERGE (associated with Manne and Richels) 1– reach conclusions that are roughly similar to those of DICE. FUND is noteworthy because of its relatively sophisticated game theoretic treatment of uncertainty. According to Tol (1996), optimal control is greater under uncertainty than under 'best guesses', co-operation than non-co-operation and 'bottom-up' than 'top-down', none of which intuitively is of great surprise.

The exception to the broad consensus described above is found in the work of Cline (1992), who concludes that aggressive abatement (GHG emissions limited to 4 Giga tonnes (Gt) compared with about 7 Gt in the 1990s) would yield a benefit to cost ratio of 1.3. The main explanations for the findings of Cline are the use of a low discount rate of 1.5 per cent (see section 4) and the assumption that policy makers are risk averse (a high damage case is weighted three times as high as a low damage case).

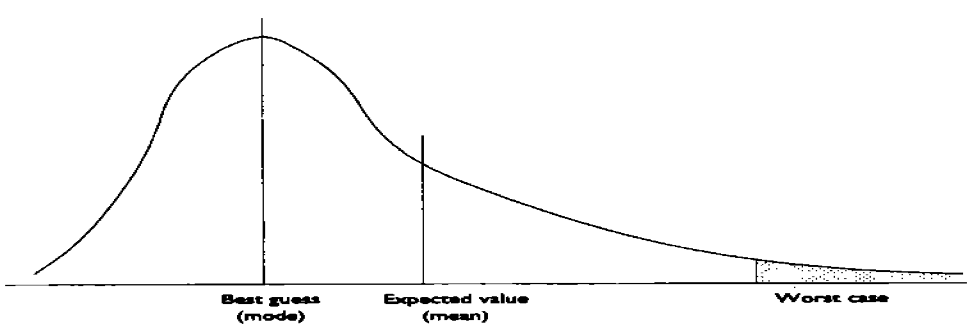
These models also provide estimates of the shadow price (marginal damage) of a tonne of carbon, which can be used in CBA (Fankhauser and Tol 1995). Estimates for the period 1991– 2000 fall in the wide range US $ 5–125 per tonne (1990 prices), rising over time due to economic growth and increasing CO_2 concentration levels. The figures are especially sensitive to the assumed discount rate.

The debate on global warming is characterised by an enormous degree of uncertainty. Some of this stems from a lack of knowledge but, on other matters, there are differences of opinion. In the IAMs referred to above, it is common for sensitivity analysis to be undertaken. The aim is to demonstrate how key model outputs vary with input changes and parameter values over plausible ranges. The model outcomes are again particularly sensitive to the value of the discount rate. There are also a small number of stochastic IAMs. Tol (1996), for instance, assigns various types of probability distribution to a number of parameters, based on which he carries out a Monte Carlo experiment with 1000 runs.

Much of the concern about global warming arises from perceived low probability-high impact events in the distant future that could be irreversible or difficult to recover from. Several catastrophe scenarios are portrayed in the literature, for example, disintegration of the West Antartic ice sheet, a redirection of the gulf stream, a runaway greenhouse effect through massive, positive feedback mechanisms and sudden non-linear changes in climate patterns. IAMs incorporate information and judgements about the mode (best guess) and sometimes the mean (expected value) of the damage function distribution but generally reveal nothing about its tail (Figure 3).

Nordhaus (1994) has grouped activities designed to mitigate the effects of uncertainty into three categories (Table 3). Insurance should probably be ruled out on grounds of 'moral hazard' since those who are most vulnerable to climate change generally know in advance of it happening.

Figure 3: The Distribution of Global Warming Damage Costs



Source: Fankhauser (1996)

Consumption-smoothing over time – putting aside resources today to consume in the future, at the time of a threshold impact – has some intuitive appeal though it is not clear how such a compensation fund would work in practice (Pearce and Warford 1993). Lastly, precautionary investments enable society to hedge against the possibility of adverse climate outcomes before major uncertainties have been resolved. The most obvious form of precautionary investment would be to increase the rate of GHG reduction in order to reduce the probability of extreme outcomes and to be better positioned should severe cuts be necessary. Other precautionary measures might anticipate the possible need to adapt to higher sea levels. Improved knowledge of chemical and physical processes and their interactions with humankind and the biosphere is likely to be of high value in helping to reduce uncertainty.

In sum, the CBA work of economists on global warming indicates, as far as measurement and valuation allow reasonable comparisons to be made, that the benefits of abatement are not significantly greater than the costs of mitigation. It suggests that the shadow price of carbon is relatively modest. The case for some measures to be taken now is largely based on the precautionary principle but there is no need for drastic action. This can be postponed until it is more certain that it is needed. The high degree of uncertainty should be considerably reduced due to advances in knowledge and understanding in the next decade (Beckerman 1995).

Table 3: Alternative Policies to Mitigate Uncertainty

Category	*Source of uncertainty*	*Policy*
1. traditional insurance	1. diversifiable (individual) risk	1.a. private (weather, crop) 1.b. social (against e.g. income losses)
2. consumption smoothing over time	2. risk of large or catastrophic loss	2. investment 'for a rainy day'
3. precautionary investments	3. uncertain scope of damage or abatement costs	3.a. precautionary abatement (higher carbon tax) 3.b. precautionary adaptation (retreat from coastline) 3.c. investment in knowledge (geophysical and social science research)

Source: Nordhaus (1994)

4. QUESTIONS OF EQUITY

The paper now shifts from questions of economic efficiency to focus on ones of equity, that is 'fairness' or 'justice'. Concerns about equity arise from considerations of the distribution of the costs of mitigation as well as of adaptation and the impacts of unmitigated global warming within current and across current and future generations. They are of an analytical, procedural and consequential nature.

Some authors ground the debate on equity and global warming on general principles of justice (Paterson 1996). For example, in one approach, it is suggested that since industrial countries historically caused the problem of global warming, they have a moral responsibility to put the situation right, that is, the polluter should pay. In another, it is argued that, if it is possible to prevent something bad from happening without sacrificing anything of comparable importance, it is morally appropriate to take action. This is the basis of classical utilitarianism associated with Bentham and finds expression in the utility maximisation goal of welfare economics. A third position is a Rawlsian one (Rawls 1973), whereby a response to global warming is just, to the extent that it improves the position of the worst-off. Most positions on global warming can be defended with reference to a number of notions of justice. Paterson (1996) derives a classification from Grubb (1995). The practical response is the outcome of a process of negotiation and political compromise.

In the standard approach to CBA it is assumed that individual preferences can be defined – according to measures of ability-to-pay (ATP) and willingness-to-pay (WTP) – compared and aggregated in money terms with a view to maximisation of some measure of output, say, GNP (Little and Mirrlees 1974). Critics argue this approach is unethical, since WTP-WTA measures reflect the unfairness of the existing distribution of income and wealth. It results in otherwise identical goods and services being valued differently, say, in different countries, for reasons of income alone.

Several approaches have been invoked to give greater weight to the preferences and needs of poorer people in the global warming arithmetic. The most elegant uses income weights, derived from the pioneering work of Squire and van der Tak (1975). Tol *et al.* (1996) take the original damage estimates of the IPPC (IPPCc 1996) and show how the calculations could be corrected, assuming three different types of welfare function and different values for the income elasticity of marginal utility, to reflect concern about inequality. In most cases, the damage cost estimates are higher. The same authors (Fankhauser *et al.* 1998), in a different approach, correct the earlier estimates of damage for differences in purchasing power. The effect is to raise non-OECD damages by 40–60 per cent and global damages by 15–20 per cent. Finally, in a third approach, the same unit values are used for developing as developed countries based on a one-for-one 'benefit-transfer'; for instance, if the OECD value of a statistical life is applied to all regions, global mortality costs increase several-fold. Such an approach, however, leads to inconsistencies in the way local and global damages are measured. But irrespective of the approach, generally all the work in this field suggests that when equity considerations are taken into account, the damage cost estimates rise by a significant margin. It partly derives from the fact that the poor South will suffer more from global warming than the rich North. Thus considerations of intra-generational equity appear to strengthen the case for mitigation.

The fact that the effects of global warming, if not mitigated, will be felt over a long period of time means that the choice of discount rate exerts a powerful influence on policy choice in which net present value calculations play a role. The discount rate is influential in the debate on the extent to which present generations should invest to safeguard the wellbeing of future generations.

Many economists subscribe to a framework derived from neo-classical growth theory:

$$d = p + ug$$

where

d = discount rate

p = rate of pure time preference

u = income elasticity of marginal utility

g = growth rate of per capita consumption

There is also a general consensus among economists that the discount rate should not be used to compensate for changes in relative scarcity of, say, environmental assets, over time. Valuation is the appropriate way to correct for this. The discount rate is also not the appropriate way for dealing with uncertainty. Nevertheless, economists disagree on several other issues related to the discount rate. There are two approaches. In the 'prescriptive' approach, which often defines d as the social rate of time preference (SRTP), p reflects the impatience or myopia of present generations and ug that future consumption should be discounted if future generations are expected to be better-off than the current generation. With p often assumed to be zero, the prescriptive approach results in a relatively low SRTP (less than 3 per cent). Economists who favour the 'descriptive' approach argue that, in order to maximise social welfare, the real rate of return (ROR) on mitigation investments should match those in the market. They propose relatively high rates of discount (5–10 per cent), according to empirical evidence on opportunity costs (6). Extreme positions are taken, on the one hand, by Broome (1992), who argues for a zero rate of discount, based on impartiality about time, and, on the other, by Beckerman (1993), with counter-arguments in favour of using the market-determined cost of loan funds.

The prescriptive approach can be interpreted as overriding revealed market preferences on ethical grounds in order to justify doing more about global warming today whereas the descriptive approach aims to maximise the conventional measure of economic growth, implicitly leaving unanswered the question of compensation to future generations. The former favours spending more today on mitigating climate change than the latter. Most of the CBA models discussed in section 3 apply market-based discount rates. For instance, Nordhaus (1994) uses 6 per cent. Cline (1992) is again the main exception – for his base case, he uses a STPR of 1.5 per cent – and this is one reason for his relatively high damage cost estimates (see Toth (1999) for a comparative analysis of the role of discounting in CBA models). The discounting issue is far from settled. Ultimately, the question of what rate to use is a political one, which cannot be solved by academic debate alone.

The FCCC (UN 1992) contains several principles and specific provisions concerning equity. Article 3.1 mentions equity in the context of burden sharing between all parties and, in particular, between developed and developing countries. It also suggests that, in the interests of equity, the present generation has responsibilities to those in the future. Article 4.2(a) also points out that equity should be applied among developed countries. Finally, Article 11.2 reflects the concern of developing countries for procedural fairness in respect of the functioning of the financial mechanism. It must also be recognised that the Parties to the Convention differ in significant ways. Although a North-South division should be applied with caution, the developing countries are generally poorer, have contributed much less to past emissions, have weaker institutions and are more vulnerable to climate change.

Notions of equity also play a major role when considering how future abatement effort should be allocated, giving rise to some of the most contentious issues in the global warming debate. It is useful to distinguish the short from the long term. In the short term, it is generally accepted that the burden of adjustment should rest with the richer North. As Shue (1992) has famously put it, 'Even in an emergency one pawns the jewellery before selling the blankets.' In the longer term, when the aim must be to involve as many countries as possible, a number of allocation principles applying different ethical frameworks have been proposed. According to the parity principle, each human being would have the same absolute right of access to the global atmosphere commons. In an approach probably similar in outcome to the parity principle, each country would have the right to emit greenhouse gases according to its basic needs. Another line of argument focuses on historical responsibilities. According to this, the problem has been caused by the North, whose prior use of a finite stock is now prejudicing the development prospects of the South. Yet another stresses the fairness of 'comparable burdens', with each country paying according to a fixed proportion of an ability-to-pay measure. By contrast, countries 'should' be willing-to-pay according to the potential, including global, damages that they face.

Assuming, for the sake of argument, that tradeable emission quotas (7) are selected as the instrument for achieving efficient abatement, the crucial distributive problem concerns the allocation of quotas in a manner acceptable to all parties (Müller 1998). The stakes would be high and the outcome determined by strategic bargaining. This issue is dealt with in section 6. Here the focus is on the allocation criteria. With the optimal economic approach of an auction ruled out on grounds of ability-to-pay, the two distributions which have attracted most interest are those based on the *status quo*, known as 'grandfathering', which subsumes the principles of willingness-to-pay and comparable burdens, and an equal per capita allocation, which subsumes the basic needs principle. In the case of the latter, the burden of adjustment would fall on the OECD; in that of the former, on developing countries. Grubb (1995) has suggested an average of the two, increasing the weighting to population over time.

Consequential and procedural equity are inseparable. The costs of inadequate participation and information are likely to be protracted negotiations with suboptimal outcomes and poor compliance with any resulting agreement. Participation in international processes can be restricted by limitations on human and financial resources though smaller countries may be able to rely on larger countries and may also benefit from NGO support. In such complex areas as climate change, many developing countries feel disadvantaged by not having adequate specialist knowledge and analytical capability.

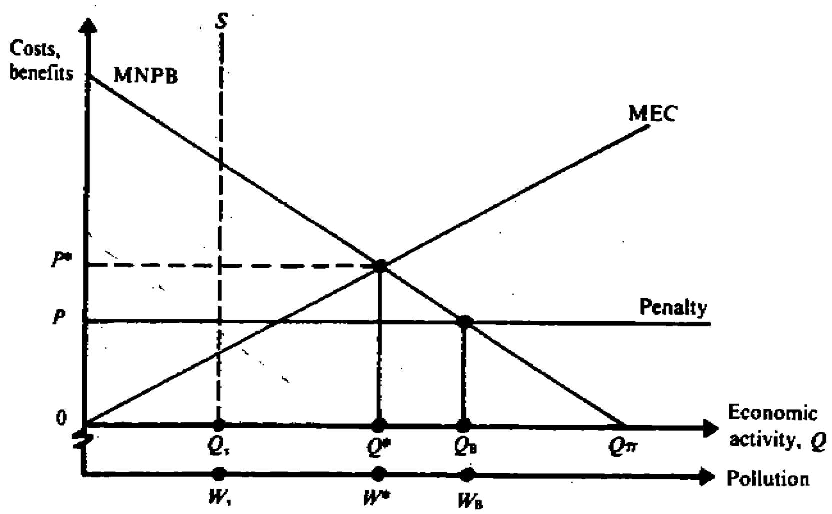
5. INSTRUMENTS OF ENVIRONMENTAL MANAGEMENT

The aim of this section is to provide an economic assessment of the possible international policy instruments for managing greenhouse gas emissions. The policy options for the international community as well as the criteria for assessing them are broadly the same as for individual countries. The main policy choice is between regulatory, 'command-and-control' standards and market-based instruments. Regulation might take the form of energy efficiency standards for electrical appliances (e.g. the European Union (EU) energy label for 'white' goods). It could involve fixed emission limits, in the tradition of the EU Large Combustion Plant Directive (EU 1994) and the EU's 'auto-oil' programme. Market-based instruments in contrast aim to influence decisions through the price mechanism. The policy choice in this regard is usually expressed in terms of taxes 'versus' tradable quotas. One tax option would be an agreement that all countries apply the same level of domestic carbon tax; alternatively, there might be agreement to a uniform international tax imposed by an international agency. With tradable quotas, participating countries would receive an allocation of rights (see Section 3), which could be exchanged at a market-determined price.

Among the criteria that might be used for assessing international policy instruments are efficiency, cost effectiveness, equity, effectiveness in achieving a stated environmental target, flexibility in the face of uncertainty, understandability to the general public and consistency with national institutions and traditions (IPPCc 1996). The focus in this section is on efficiency and cost effectiveness. An efficient outcome in economic terms is one in which the standard neo-classical marginal conditions are satisfied. A solution is cost effective if it is achieved at minimum cost, regardless of the efficiency of the outcome.

It is only by accident that standard setting is efficient. To see this, consider the familiar pollution diagram (Figure 4), taken from Pearce and Turner (1990).

Figure 4: Environmental Standards

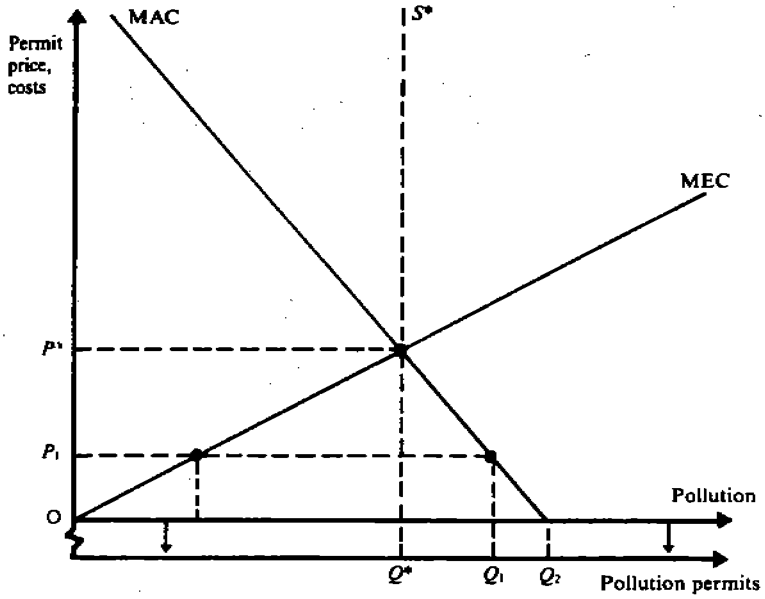


Source: Pearce and Turner (1990)

The standard is set at S, equivalent to Qs of economic activity and Ws of pollution. This is below the optimum of W*. Typically, standards are associated with penalties, in this case P. If the penalty is certain – the polluter can expect to be successfully prosecuted – it pays to pollute to WB. Thus there will be either too little or too much pollution.

Imposing a tax per unit of pollution on the polluter would have the effect of shifting MNPB left and downwards. The polluter will now maximise net benefits at a lower level of output. At the optimal output Q* – and level of pollution – the 'Pigouvian Tax' (8) is equal to the marginal pollution damage MEC. The polluter pays a charge equal to the tax times the quantity of pollution. There is a continuing incentive to reduce pollution. Whether this is judged as a fair arrangement, however, depends on how society views the assignment of property rights. According to the 'polluter-pays' principle, the polluter has no right to use the environment as a 'sink' and the tax might be considered as a charge for using common property. The problem can also be analysed in terms of abatement costs (Figure 5).

Figure 5: Marketable Permits



Source: Pearce and Turner (1990)

MAC is the marginal abatement cost curve and, at the optimal level of pollution, MAC = MEC. MAC is the analogue of MNPB, where abatement equipment rather than output reductions are used to reduce pollution. Here MAC can be interpreted as the demand curve for tradable permits and Q* the optimal quantity issued by the authorities.

Despite their many virtues, pollution taxes have not been widely used in a national context. They have found more favour in Europe than in the USA (Howe 1994). Polluters have contested the fairness of taxing the optimal level of pollution; experts have argued about the nature of the external cost function; and, regulators have often favoured a more interventionist policy. In the context of global warming, there have been several proposals for a tax on the carbon content of fuel. Barrett (1990), in an OECD study, has assembled the early estimates. Though comparing the various studies is difficult, his survey suggested that carbon taxes of about US$ 100 per tonne, or around a 65 per cent increase in the price of a US$ 20 per barrel of oil, would be adequate to at least stabilise CO_2 emissions at 1990 levels by 2005.

Pearce (1991) describes the advantages and disadvantages of a carbon tax in the context of global warming. Among the advantages, it would generate a large volume of revenue, which might be used to reduce incentive-distorting taxes on capital and labour, the so-called 'double-dividend'. If the tax is levied internationally, it might be a source of revenue for persuading developing countries to enter into GHG reduction commitments. It also has static and dynamic efficiency incentive characteristics. Among the disadvantages, a carbon tax, in the absence of reasonable knowledge about standard and cross fuel elasticities, will be 'hit-and-miss' in regard to a given CO_2 emission reduction target. Carbon taxes themselves will impose a 'dead-weight loss' though this has been estimated as small for a 'small' tax. Finally, there may be political resistance to a new tax, partly because a carbon tax might be regressive.

The use of tradable permits has a number of attractions. By giving polluters a chance to trade, the total costs of pollution abatement are minimised. Low abatement cost polluters sell and high cost polluters buy permits. The authorities can tighten or loosen the standard by withdrawing or issuing permits and, in a truly free market, third parties, such as environmental groups, can exert an influence. The only noteworthy examples of emission trading schemes are found in the USA (Hawkins 1998): the Environmental Protection Agency (EPA) Emissions Trading Programme; the EPA Lead Trading and Banking Programme; and, the Acid Rain Programme. The results are mixed. Probably the programme that has performed the best is the Acid Rain Programme. Interestingly, it is closest to the textbook model. It was carefully planned by the EPA. The market has grown to the point where the Chicago Board of Trade deals in futures. Cost compliance – indicated by the price of sulphur permits in the range US$ 70-200 per ton – is considerably below expectations, of US $ 1000 per ton.

In the idealised model, an emission tax is equivalent to a marketable permit arrangement. The same information is required to specify both. In one case the price is exogenous and the quantity endogenous, in the other the properties are reversed. This neat result, however, no longer holds when uncertainty is introduced. An exhaustive treatment of the subject can be found in Baumol and Oates (1988), following a substantial literature. In summary, neither instrument is favoured when there is uncertainty with respect to the benefits of abatement (MEC). In a seminal paper, Weitzman (1974) showed that where there is uncertainty about abatement costs (MAC), the two instruments are equivalent only if the slopes of the marginal benefit and cost curves are equal. If the slope of MAC (MEC) is greater than that of the MEC (MAC), then marketable permits (taxes) would be preferred.

The empirical evidence is not conclusive on this point. On the one hand, marginal abatement costs are likely to be steep once abatement becomes substantial though the curve may flatten out if a 'backstop technology ' is available. On the other hand, there is concern that a damage threshold exists at high levels of emissions. In fact, the two instruments are not mutually exclusive and, with a high degree of uncertainty, a mixed system may be preferable. For example, a quantity of permits may be issued. In addition, there would be a tax. If the costs turn out higher than expected, polluters may pay the tax rather than buy permits, the tax thus serving to cap the marginal abatement cost.

International negotiations on global warming have focused on a tradable quota system. This appears to be for practical rather than theoretical reasons though none of the arguments are compelling. An international tax would be an infringement of national sovereignty. It could easily be rendered ineffective in participating countries by, for instance, a reduction in existing energy taxes. Lastly, a competitive advantage would accrue to those countries which failed either to apply or enforce the tax (see Section 6 on 'leakage').

A number of abatement costs studies comparing market with command-based approaches suggest that countries could save large sums by using a tradable quota system to meet emission reduction commitments. The findings are summarised in Hahn (1998). The savings are in the range 5–100 per cent relative to the case with no trading for different countries under different assumptions. In practice the gains will be substantially less because of market imperfections, not least due to government market interference. Hahn recommends testing various alternative institutional arrangements. Barrett (1999) also argues that the success of international agreements on GHG abatement ultimately will depend on whether implementation can be made cost effective. The estimates which he quotes suggest that shifting one tonne of abatement from OECD to developing countries would save about US$ 100.

6. INTERNATIONAL AGREEMENTS

For an understanding of the economic aspects of international agreements on the environment it is necessary to turn to game theory (9). The literature considers two issues: the benefits of co-operation and the formation and stability of coalitions. Game theory is concerned with the general analysis of strategic interaction (Varian 1996). It asserts that the pair of strategies of two players, I and II (say, Annex I and Annex II countries of the Kyoto Protocol), is a 'Nash' equilibrium if I's choice is optimal, given II's choice and II's choice is optimal given I's choice.

One problem with the outcome of a Nash equilibrium is that it is not necessarily Pareto efficient. This can be seen from consideration of the 'prisoner's dilemma' game, reformulated to illustrate the problem of global warming. The 'payoff' matrix for this game is as follows. If all countries abate, each group gains 3, for argument sake. If neither abate, each gains 1. Globally, it is better to abate than not to abate. But if I abates and II does not, I gains 0 and II gains 6. The same is true in reverse.

		Annex II	
		Abate	Not Abate
Annex I	Abate	3, 3	0, 6
	Not Abate	6, 0	1, 1

Annex I countries reason that if Annex II countries abate, it is better not to abate (6 is greater than 3). If Annex II countries do not abate, it is again better for Annex I countries not to abate (1 is greater than 0). Therefore, the dominant strategy for Annex I countries is not to abate. The same argument holds for Annex II countries. The Nash equilibrium is for all countries to not abate. But if all countries abated, all countries would be better off. The problem is how to arrive at this outcome.

Having agreed to abate, there is a temptation to cheat. One way possibly to resolve the dilemma is to assume that the game is repeated an infinite number of times. In this situation, a defection by one player, on one round, can always be punished by the other player, on the next round. This is known as 'tit-for-tat' and is a common strategy in real-world oligopolies, such as airline pricing. Alternatively, the players may negotiate a set of penalties for non-compliance. Even if institutional arrangements can be agreed, there are monitoring, verification and enforcement problems with using penalties in an international context. Not surprisingly, this matter was left open in the Kyoto Protocol. It remains for 'The Conference of the Parties .... (to) approve appropriate and effective procedures and mechanisms to determine and address cases of non-compliance .... including .... an indicative list of consequences' (Article 18, UN 1997) (10).

The 'free rider' problem is similar but not identical to that of the prisoner's dilemma. It arises in the case of a public good (see Section 2). Both Annex I and Annex II countries would prefer to stabilise GHGs but each hopes this might be achieved by mitigation on the part of the other. A free riding matrix, using different pay-offs for the sake of argument, is set out below.

		Annex II	
		Abate	Not Abate
Annex I	Abate	-50, -50	-50, 100
	Not Abate	100, -50	0, 0

Suppose that each group of countries values a stable atmosphere at 100 and that the cost of stabilisation is 150. If the atmosphere is stabilised by one group of countries, it is impossible to exclude the other from the benefits. If

Annex I countries alone stabilise the atmosphere, they get a benefit of 100 for a cost of 150, resulting in a loss of –50. Annex II countries get a benefit of 100 for free. The same holds for Annex II countries if they assume sole responsibility for the atmosphere. The dominant strategy for each group is not to abate and to free ride on the actions of the other but this is ultimately self-defeating. Such action results in a welfare gain of zero. However, welfare can be increased by 50 if either one or other of the groups abates. This can be achieved by a 'side payment' between the two parties; for instance, if Annex I countries pay 51 to Annex II countries to abate.

The global warming policy debate has characteristics of both the prisoner's dilemma and the free-rider problem. An introduction to game theory would seem to support intuition that there are likely to be gains from international co-operation in the field of global warming but that successful agreements may prove illusive. Some of the literature on these issues is reviewed below.

Ulph (1998) provides a proof that a non co-operative equilibrium will have higher GHG emissions than a co-operative equilibrium and that there are substantial gains from co-operation. In the non co-operative case, each country aims to maximise its own welfare, by setting its own marginal benefit of abatement equal to the marginal cost of abatement. In the co-operative case, the aim is to maximise global welfare, by setting the global marginal benefits of abatement equal to each country's marginal cost of abatement (11). The gains from co-operation are large when the slope of the global marginal benefit function approximates the slope of each country's marginal abatement cost curve and both slopes are large. An agreement will be stable if, for each country, the reduction in costs from withdrawal would be more than offset from the resulting loss in benefits due to a weakening of the agreement caused by its defection.

These results carry over into models incorporating uncertainty and learning. The gains from co-operation are likely to be larger when learning is possible since information has a positive value. By contrast, if some countries are expected to gain from global warming whilst others lose, information may make it more difficult to reach an international agreement. It is therefore plausible, if somewhat surprising, that information in this context has a negative value.

But if the gains from co-operation are substantial, it is unlikely that many countries will voluntarily agree to co-operate due to the free-rider problem (Barrett 1992). Co-operation may be fostered if participants have opportunities to identify cost-effective solutions through trade in emissions rights (see Sections 5 and 7). Heal (1992), however, argues that a successful coalition will comprise a minimum number of countries, to provide for the fact that each country benefits not only from its own abatement but that of others. In this view, the abatement activities of each country should aim to reinforce the activities of others, for instance, through co-operation on technology research.

Simulation work, however, suggests the gains from co-operation are modest though the results are very sensitive to a number of assumptions, such as the form of the damage function. For instance, work by Fankhauser and Kverndokk (1992) suggests optimal emissions reductions with co-operation of 2–15 per cent world-wide, yielding global welfare gains of 0.2 per cent GDP. Of five regions, the biggest gains are registered by the 'rest of the world' (developing countries) and the OECD whereas China and the USSR suffer losses. The USA neither gains nor loses. Though a socially optimal treaty is beneficial for the world it may only be achieved if side payments are offered to China and the USSR. In other words, a beneficial international agreement involving both developed and developing countries is likely to be unstable without side payments. The simulations also show that, apart from the OECD, there is little incentive for unilateral reductions. The results are broadly consistent with the real world.

Practically the success of any agreement in terms of emissions abatement will depend on the degree of leakage. 'Leakage' is defined as the ratio of the increase in emissions in non-participating countries to the associated reductions in participating countries. The figure could be as high as 10per cent. Leakage may be due to the relocation of emitting industries from participating to non-participating countries in order to avoid restrictions as well as to a general rise in demand for fossil fuels in developing countries due to a fall in prices. The greater the participation rate, the larger the opportunities for cost-effective trade in rights and the smaller the degree of leakage.

7. AN INSTITUTIONAL POSTSCRIPT

The negotiations which resulted in the FCCC (1992) and its sequel, the Kyoto Protocol (1997), were influenced not only by the science of global warming but to some extent by all the relevant theory and application of environmental economics reviewed in the main body of this paper.

The decisions taken at Rio de Janeiro and Kyoto suggest that, for the most part, the international community judge that the benefits from a modest degree of GHG abatement are likely to exceed the costs. But although the balance of evidence suggests that humankind is influencing the climate, there is, probably rightly, considerable reluctance to take dramatic action now. There is a high degree of uncertainty about the scientific and socio-economic processes associated with global warming. In such circumstances, initially, action should focus on 'no-regrets' measures and there is a premium on greater knowledge about the subject and on improvements in carbon efficient technologies. As a matter of fairness and in consideration of their own interests, the generally richer Annex I countries have agreed to bear differentially the main costs of an initial response to the problem of global warming. To fulfil their commitments at minimum costs and for other practical reasons, a system based on tradable emission quotas has been chosen as the preferred international policy instrument. In the Kyoto Protocol, three types of trades are envisaged: 'joint implementation' between Annex I countries (Article 4); 'joint implementation' between Annex I and non-Annex I countries through the 'Clean Development Mechanism' (Article 12); and, emissions trading between Annex I countries (Article 17). International trading also provides each participant with maximum flexibility of policy choice at the national level. The literature suggests that international co-operation on global environmental issues is likely to yield considerable benefits but that enforcement will prove difficult. Some countries at least appear to believe in the merits of co-operation though the Kyoto Protocol is only a beginning. Developing countries – which by the end of the first commitment period (2012) will emit a similar quantity of carbon dioxide emissions as Annex I countries – will need to be persuaded to enter into commitments themselves. Any international agreement must be supported by a credible regime of monitoring and enforcement.

The threat of global warming presents a huge challenge as well as opportunity for the international financial institutions (IFI). The issues to which global warming gives rise must be addressed in a satisfactory way if the IFIs are to fulfil their overarching obligations to promote sustainable development. It is in the financial interests of the IFIs to ensure that their clients are well informed and take appropriate action concerning global warming. The field of global warming is one in which the IFIs can add value and be catalysts for change as well as offering considerable potential for viable financing. It is a topic of sufficient importance to merit a policy in its own right. The policy response should include at least four broad areas in which differentially each IFI can play a useful role. These derive from the findings of the main body of the paper.

First, the IFIs can have most immediate impact in the field of global warming through their project financing decisions regardless of progress on international agreements. Section 3 suggests the type of project which should be financed and Section 5 provides the justification for promoting trade in project-generated carbon quotas. Opportunities for GHG emission abatement can be found in all sectors. A pro-active approach, combining tailored technical and financial support, will be needed to take some of these opportunities forward. Some types of investment may be justified in their own right ('no-regrets') but nevertheless merit increased attention (for example, energy conservation and efficiency). Other types (for example, renewable energy and afforestation) may, either completely or partially, be justified in global warming terms but in some cases need financial support. Projects should be promoted which facilitate adaptation to global warming as well as compensate for activities which increase GHG emissions.

With reference to the Kyoto Protocol, particular attention should be given to investments that comply with individual country abatement and adaptation programmes and the principles of the flexibility mechanisms. Carbon trading among Annex I countries as well as between Annex I and developing countries should be promoted by helping to identify, finance and monitor projects which generate valid quotas.

Second, the IFIs should seek through changes in their policies and procedures to mainstream global warming considerations into all their activities. They should demonstrate their commitment to bringing about a reduction in GHGs by starting with their own internal housekeeping. More generally, each IFI should introduce some form of carbon budgeting in order to describe and justify its global warming footprint in the same way that it reports its annual financial performance. Thus the net effect in terms of say, tonnes of CO_2-equivalent, should be estimated at appraisal and subsequently monitored for each project. In this way each IFI should demonstrate its commitment to safeguarding the atmosphere in the spirit of the approach to sustainable development described in Section 1. Moreover, project decisions based on CBA should include the quantification and valuation of global warming externalities in accordance with the theory and empirical evidence discussed in Sections 2 and 3.

Third, the IFIs are well placed to encourage the development of the international institutional framework to support concrete action in the field of global warming. Section 6 pointed out the gains from international co-operation as well as the difficulties of ensuring compliance with international commitments. Apart from activities related to investment (see below), the IFIs could do a number of things to foster the Kyoto Protocol. For example, they could assist the transition countries of Annex I to fulfil their annual reporting requirements (Article 7, UN (1997)) and to formulate national mitigation and adaptation programmes (Article 10). In the case of developing countries, they could promote the transfer of environmentally sound technologies and assist with capacity building (Article 10). They could also contribute towards the preparation of operational guidelines in respect of the three flexibility mechanisms (Articles 4, 12 and 17) and more generally develop incentive mechanisms to encourage developing countries to assume commitments themselves.

Fourth, the natural starting point for each IFI is to provide its clients with reliable information and objective advice to help build awareness of the complex issues relating to global warming. To be able to do this, each IFI needs to further develop its own internal knowledge and understanding of the subject as well as experience in dealing with the practical problems to which it gives rise. Section 4 has pointed out the likely high returns to advances in knowledge and understanding of the subject.

NOTES

1 Probably only one other environmental issue, bio-diversity, is of equivalent global significance. The greenhouse effect and the loss of bio-diversity share several features in common. They have major implications for future as well as present generations; there is considerable uncertainty about what is happening and the likely effects, though on balance these are considered adverse; the world is experiencing a period of unprecedented change, which is probably irreversible (see Wilson (1992) on bio-diversity).

2 This section owes much to the collaborative work on sustainable development of the Centre for Social and Economic Research on the Global Environment (CSERGE) and the World Bank (see, for example, Atkinson *et al.* (1997) and Pearce and Warford (1993)).

3 Imagine, in the case described, that the property rights are assigned to the polluter. She will start at QΠ but at that level the sufferer will be willing to pay iQΠ to prevent the pollution, so the polluter accepts and moves to f. Again, the sufferer is willing to pay the polluter more than she gains from polluting and the polluter moves to j; and, so on, until no further bargains can be struck, at Q*. The same line of argument holds if the initial rights are assigned to the sufferer; the distribution of income, however, will differ according to the initial assignment of rights.

4. The costs of GHG damage differs from the benefits of GHG abatement due to secondary benefits, such as the effects of deforestation on bio-diversity and improvements in local and regional air quality due to the use of fossil fuels (Pearce 1992).

5. Pareto efficiency exists when there is no alternative allocation of resources that makes everyone at least as well off and makes some people

strictly better off. If there are losers not compensated by gainers, the efficiency improvement in this sense is only a potential one.

6. In a perfect world, the social rate of time preference would equal the opportunity cost of capital and both would equal the market rate of interest. In reality, mainly due to distorting taxation, the ROR is higher than the SRTP.

7. It is customary to use 'quotas' to describe internationally traded emission allowances and 'permits' to describe allowances which are domestically traded.

8. In the Economics of Welfare, Arthur Pigou (1877–1959) proposed a tax as a suitable means for equating private and social cost.

9. Gibbons (1992) provides a good theoretical exposition of game theory.

10. The example of the Montreal Protocol is often cited. It is doubtful, however, whether the trade-related incentives it contained would be appropriate in the case of global warming (see Barrett (1999)).

11. These are often referred to as the 'Samuelson conditions', after pioneering work by Paul Samuelson (1954) in the field of public sector economics.

ANNEX

The Scientific Background

The natural greenhouse effect was first described by the scientist Jean Fourier in the 1820s. Short wave radiation from the sun can pass easily through the atmosphere whereas long wave radiation from the earth is partially absorbed by a number of trace gases. Acting like a radiation blanket, trace gases help to keep the temperature of the surface of the earth, which adjusts to maintain the radiation balance, about 33°C higher than the minus 18°C it would be otherwise. The main natural greenhouse gases (GHGs) are water vapour, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and ozone (O_3). Since the Industrial Revolution, human activities have given rise to a significant increase in natural GHG emissions, apart from water vapour, as well as additional emissions of human-made GHGs (halocarbons, such as chlorofluorocarbons (CFCs), and related compounds (such as sulphur hexafluoride (SF6)). As a result, there has been a change in the radiation balance – known as 'radiative forcing' – and the potential for an increase in the earth's temperature. Svante Aarhenius at the turn of the twentieth century described this as the 'enhanced' greenhouse effect. Interest has focused on the role of CO_2. Although the global warming potential of CO_2 is considerably less than that of other GHGs, the volume of emissions from the production and use of fossil fuels and land-use changes, such as deforestation, is relatively large and CO_2 has a long lifetime.

The most authoritative account of the science of climate change can be found in the 'Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPPC)' (IPPCa, 1996; see also Houghton (1997)). The IPPC was set up jointly by the World Meteorological Organisation and the United Nations Environment Programme in 1988. Scientists use large, complex global climate models (GCMs) to describe and forecast the relationships between the atmosphere, the earth and the oceans.

One of the most advanced GCMs is the Hadley Centre model (UK Meteorological Office (MO) 1997). Though confidence in climate models has increased, all such modelling faces major difficulties, including a poor understanding of several key climate processes, such as 'feedback' mechanisms (for example, cloud cover; see Barry and Chorley (1998) for an introduction to climate and weather), the short historical records and computer constraints. In respect of past patterns, it is hard to disentangle natural climate variability from underlying trends and regional climate simulation generally is hampered by the coarse resolution of the models. Estimates of the future remain highly uncertain, not least due to the non-linear nature of the climate system.

Nevertheless a scientific consensus is developing. As far as recent events are concerned there is a convergence of professional opinion on a number of important findings. 'The balance of evidence suggests that there is a discernible human influence on global climate' (IPPCa 1996). 'The twentieth century global mean temperature is at least as warm as any other century since at least 1400' (IPPCa 1996). 'It is unlikely that global mean temperatures have varied by more than 1°C in a century' (IPPCb 1996) during the last 10,000 years. Finally, 'the temperature rise over the last decade or so has been outside the range of natural variability' (MO 1997).

There is also broad agreement on likely future climate change at the global level, according to an emissions – radiative forcing – GHG atmospheric concentration – temperature chain of causation. The IPPC has produced six scenarios based on a range of population, economic growth, energy supply and other assumptions to the year 2100. These and the main results are summarised in Mabey *et al.* (1997). Global mean temperature is estimated to increase in the range 0.8–4.5°C, with a 'best estimate' under 'business-as-usual' of 2.4°C (IPPCb 1996). About 70 per cent of the warming is attributed to CO_2. Changes in temperature as well as precipitation will vary by region. Global warming will be associated with a rise in sea-level due to the thermal expansion of the oceans and ice-melt (estimated range 13–94 cm, 'best estimate' 66 cm) and probably greater severity and frequency of extreme weather events, such as tropical storms. 'Surprise' events, such as a reversal in the thermohaline circulation, which keeps the North Atlantic ocean several degrees warmer than otherwise, and a collapse of the West Antarctic ice sheet cannot be ruled out. Climate change modelling is also used to estimate the effect of an increase in a given atmospheric concentration of GHGs and to illustrate the relation between emission profiles and concentration levels. Higher emissions today require steeper emissions cuts tomorrow for a given target concentration level. Temperature is estimated to rise by 2.5°C sometime in the twenty-second century for the benchmark doubling of CO_2 concentration, which will be reached by 2050 under 'business-as-usual'.

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