

Global Crises, Global Solutions

Edited by

BJØRN LOMBORG



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Climate Change

WILLIAM R. CLINE

Introduction

This chapter is part of the Copenhagen Consensus initiative of Denmark's National Environmental Assessment Institute. This initiative seeks to evaluate the costs and benefits of alternative public policy actions in a wide range of key policy areas. For comparability, each of the studies in this programme identifies a limited number of policy actions and examines their respective costs and benefits. This chapter examines the issue area of abatement of greenhouse gas emissions to limit future damage from global warming. Three policy strategies are evaluated: (a) an optimal, globally coordinated carbon tax; (b) the Kyoto Protocol; and (c) a value-at-risk strategy setting carbon taxes to limit exposure to high damage. First, however, a considerable portion of this chapter must be devoted to the conceptual framework and key assumptions used in modelling costs and benefits from abatement of global warming.

The next section of this study briefly reviews the state of play in the scientific and international policy deliberations on global warming. It summarises the key findings of the 2001 review of the Intergovernmental Panel on Climate Change (IPCC) and reviews the status of the Kyoto Protocol. The next section discusses crucial methodological components that can drive sharply contrasting results in cost-benefit analyses (CBAs) of global warming abatement, including especially the question of appropriate time discounting for issues with century-scale time horizons. The next section briefly reviews the findings of my own previous studies on this issue as well as those of a leading climate-economic modeller. The next section sets out the model used in this study for analysis of the policy strategies: an adapted version of the Nordhaus and Boyer (2000) DICE99 model. Further details of this

adaptation are presented in the appendix (p. 39). The next three sections present this study's CBAs of each of the three policy strategies considered, and the final section draws an overview on policy implications.

The State of Global Warming Science and Policy

The 2001 IPCC Scientific Review

For some two decades the central stylised fact of global warming science has been that the 'climate sensitivity parameter' (hereafter referred to as CS) is in a range of 1.5°C–4.5°C equilibrium warming for a doubling of atmospheric concentration of carbon dioxide from pre-industrial levels.¹ The 2001 international review (Third Assessment Report, TAR) did not change this benchmark (IPCC 2001a). However, it did increase the amount of expected realised warming by 2100.² Whereas the 1995 Second Assessment Report (SAR) had projected that by that date there would be realised warming above 1990 levels of 1.0°C–3.5°C, the TAR raised the range to 1.4–5.8°C. This increase was primarily the consequence of lower projections than before for future increases in sulphate aerosols (which reflect sunlight and thus have a cooling influence) in light of increased expectation that

¹ 'Equilibrium' refers to the level attained after allowance for the time lag associated with initial warming of the ocean (ocean thermal lag), typically placed at some thirty years. Note that atmospheric carbon dioxide has already risen from 280 to 365 parts per million (ppm), corresponding to a rise in the atmospheric stock of carbon from 596 to 766 billion tons.

² 'Realised warming' is less than committed warming at any point in time because of ocean thermal lag.

developing countries will follow industrial countries in curbing sulphur dioxide pollution (Hebert, 2000; Barrett, 2003, 364).

Other main findings of the 2001 review include the following. Global average surface temperature rose by a central estimate of 0.6°C from 1861 to 2000, up by 0.15°C from the corresponding SAR estimate through 1994.³ '[M]ost of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations' (IPCC 2001a, 10).⁴ Snow cover has 'very likely' declined by about 10 per cent since the late 1960s. There was 'widespread retreat of mountain glaciers' in the twentieth century and the global average sea level rose 0.1–0.2 m. Since the 1950s, the thickness of Arctic sea ice in late summer – early autumn has likely decreased by 40 per cent. It is very likely that precipitation increased 0.5–1.0 per cent per decade over the twentieth century in the mid- and high latitudes (>30°) of the Northern Hemisphere and by 0.2–0.3 per cent per decade in tropical areas (10°N–10°S), but that rainfall decreased by about 0.3 per cent per decade over sub-tropical areas in the Northern Hemisphere (10°N–30°N). The report judged that it was 'likely' that during the twenty-first century there would be 'increased summer continental drying and associated risk of drought', an 'increase in tropical cyclone peak wind intensities', and an 'increase in tropical cyclone mean and peak precipitation intensities' (IPCC 2001a, 15).

The 2001 report based the range of projected warming on six benchmark scenarios (table 1.1). In

³ The earth's surface temperature changed little from 1860 through 1910, then rose relatively rapidly and steadily through 1940. Thereafter there was a period of about four decades of small but relatively steady temperature *decline*, followed by a return to a renewed and more rapid warming trend since 1980 (IPCC 2001a, 3).

⁴ The report used 'likely' for 66–90 per cent chance, and 'very likely' for 90–99 per cent chance.

⁵ The baseline used here is the same as in Cline (1992). This shows emissions at 22 GtC in 2100, close to the 24.1 GtC average for the IPCC's A1B, A1F1 and A2.

⁶ Moreover, with the more rapid exhaustion of oil and gas reserves than of coal, the carbon intensity of fuel could easily rise toward the later part of the twenty-first century, as coal generates almost twice as much in carbon emissions per unit of energy (26 kg per mn British thermal units (BTU)) as natural gas and about one-quarter more than oil (Cline 1992, 142).

Table 1.1. IPCC Emissions Scenarios (GtC), 2050 and 2100

Case	Description	Emissions in:	
		2050	2100
A1B	Rapid growth, population peaking mid-century, convergence, balanced fossil–non-fossil energy	16.0	13.1
A1T	Same as A1B but non-fossil technology emphasis	12.3	4.3
A1F1	Same as A1B but fossil-intensive technology	23.1	30.3
A2	Continuously rising population, slower growth, less technological change	16.5	28.9
B1	A1 growth and population; sharper decline in materials intensity; cleaner, more resource-efficient technologies	11.7	5.2
B2	Continuously increasing population, slower growth	11.2	13.8

Source: IPCC (2001a, 14–18).

the scenario with high economic growth and fossil-fuel intensive technology (A1F1), global emissions from fossil fuels and industrial processes multiply from 6.9 GtC (bn tons of carbon) annually in 2000 to 30.3 GtC by 2100. In contrast, two of the scenarios based on optimistic assumptions about the shift toward non-fossil technology (A1T and B1) show emissions peaking at about 12 GtC by mid-century and then falling back to 5 GtC or less by 2100. The wide range of projected emissions and hence atmospheric concentrations, combined with the range of CSs in the various climate (general circulation) models, generates the relatively wide range of projected possible warming by 2100. Although the report suggests that each of the scenarios is equally likely, the analysis of this study will apply a path that is close to the average of scenarios A1B, A1F1, and A2).⁵ The scenarios with a sharp drop in carbon intensity (A1T and B1) are inconsistent with a business as usual baseline in which there is no carbon tax (or emissions ceiling) to provide an economic incentive for carbon-saving technological change.⁶

The central message of the 2001 IPCC scientific review is that the grounds for concern about global

warming have strengthened rather than weakened. There is a greater degree of certainty than in earlier reviews that the warming observed in the past century is largely anthropogenic, and the range for projected warming over the twenty-first century has been ratcheted upward rather than diminished, and by an especially large increment (by 2.3°C) at the high-warming end.

Kyoto Protocol Impasse

The state of play in international policy action on global warming is one of impasse. At the Rio Earth Summit in June of 1992, some 150 countries agreed to the Framework Convention on Climate Change (UNFCCC). The agreement did not set hard targets for emissions, however. Two implementing Conferences of Parties followed, at Berlin in 1995 and Kyoto in 1997. The Kyoto Protocol set quantitative emissions ceilings for industrial countries (including Russia), but set no limits for developing countries (most importantly, China and India). Although US President Clinton signed the treaty in November 1998, he did not submit it to the Senate for confirmation, recognising that he could not obtain the required two-thirds majority. In March 2001, President Bush rejected the Kyoto Protocol, on the grounds that the science was uncertain and that the targets could be costly to the US economy. In addition, there was a strong sense in the US Congress that any international treaty would have to include developing countries in commitments on emissions ceilings; and the US Senate had voted 95–0 in the summer of 1997 that the USA should not sign any agreement that failed to impose emissions limits on developing as well as industrial countries and that would harm US interests (Barrett 2003, 369–71).

Despite the US refusal to ratify the Kyoto Protocol, by March 2001 there were eighty-four countries that had signed the agreement, and by November 2003 there were eighty-four signatories and 120 countries that had ratified it (UNFCCC 2004). However, to take effect the Protocol required not only that at least fifty-five countries sign, but also that countries accounting for 55 per cent of the 1990 total carbon emissions from Annex I parties (industrial and transition economies) did so. Russia

has been the key to implementation, because in the absence of US adherence, without Russia's participation the emissions threshold cannot be reached. In early December 2003, Russia's President Putin reaffirmed earlier reports that he did not intend to sign the Protocol (*The Guardian*, 5 December).

Rejection of the Protocol by both the USA and, apparently, Russia leaves little in place for international abatement other than plans adopted by some countries unilaterally. However, these self-imposed limits have largely not been met. The EU announced in October 1990 that by the year 2000 it would constrain emissions to their 1990 level; however, by 1992 it clarified that it would impose its carbon tax policy toward this end only if other OECD countries also did so, including the USA and Japan (Barrett 2003, 368).

The costs and benefits of the Kyoto Protocol are considered below. However, at present it is questionable whether the protocol remains of relevance. It would seem more likely that the international community will need to return to the negotiating table to arrive at a different type of agreement that will be adopted by all of the key players, including the USA and Russia. It is possible that an arrangement for nationally collected and internationally coordinated carbon taxes, including at least the major developing countries (and albeit perhaps with some later phase-in), could form the basis for such a regime. This is the underlying approach considered in the first and third policy strategies examined below.

Core Analytical Issues

Time Discounting

Before proceeding to the specific CBAs, it is first necessary to consider the issues and debates involved in the most important dimensions of the analysis. Perhaps the single most important and controversial conceptual issue in analysing global warming policy is *how to discount future costs and benefits* to obtain comparable *present values for policy judgements*. Most issues of public policy involve actions with costs and benefits spanning a few years or, at most, a few decades. Although the scientific analysis on global warming at first

focused on the benchmark of a doubling of carbon dioxide concentrations, which was expected to occur within a few decades, by now the standard time horizon for primary focus has become at least one century. The principal scenarios and projections in the 2001 IPCC review were thus for the full period through 2100, and some additional analyses referred to effects several centuries beyond that date. Cline (1991) was the first economic analysis to propose that the proper time horizon for consideration was three centuries, on the basis that it is only on this time scale that mixing of carbon dioxide back into the deep ocean begins to reverse atmospheric buildup (Sundquist 1990). Cline (1992) estimated that on a time scale of 300 years, plausible emissions and build-up in atmospheric concentrations of carbon dioxide and other greenhouse gases could cause warming of 10°C even using the central (rather than upper-bound) value for the CS.

Typical economic analyses of costs and benefits tend to apply discount rates that simply make effects on these time scales vanish, for all practical purposes. For example, discounting at even 3 per cent annually causes \$100 two centuries in the future to be worth only 27 cents today. Yet the essence of the global warming policy is taking potentially costly actions at an early date in exchange for a reduction of potential climate damages at a later date. The damage effects stretch far into the future, in part because they begin to occur with a lag of some three decades after the emissions (because of ocean thermal lag), but more importantly because they are recurrent annually over a span of some two centuries or more because of the time of residence of carbon dioxide in the atmosphere. The asymmetry in the timing of costs and benefits of action, when combined with the vanishing-point compression of present values of century-distant effects, means that casual application of typical discount rates can introduce a strong bias against any preventive action.

Cline (1992) sets out an approach to time discounting that addresses this issue while remaining fully within the tradition of the literature on social CBAs.⁷ The key to this approach is to adopt zero as

the rate of time discounting for ‘pure time preference,’ or ‘myopic’ preference for consumption today over consumption tomorrow even when there is no expectation of a higher consumption level tomorrow. Ramsey (1928) called discounting for pure time preference ‘a practice which is ethically indefensible and arises merely from the weakness of the imagination’ (1928, 543). A second component of time discounting still remains valid in this approach, however: the discounting of future consumption on the basis of an expectation that *per capita* consumption will be rising so the marginal utility of consumption will be falling, or ‘utility-based discounting’.

The proper rate at which to discount future consumption is thus the Social Rate of Time Preference, or SRTP, where:

$$(1) \quad \text{SRTP} = \rho + \theta g,$$

where ρ is the rate of ‘pure’ time preference, θ is the ‘elasticity of marginal utility’ (absolute value) and g is the annual rate of growth of *per capita* consumption (Cline 1992, 1999). Most empirical research places θ in the range of 1–1.5, meaning that when *per capita* consumption rises by 10 per cent (for example), the marginal utility of an additional unit of consumption falls by 10–15 per cent. It is evident from 1) that if the future is considered to be a bleak outlook of perpetual stagnation at today’s levels of global *per capita* income (i.e. $g = 0$), and if there is no ‘pure’ time preference ($\rho = 0$), then there would be no discounting whatsoever (SRTP = 0). If instead *per capita* consumption is expected to grow consistently at, say, 1 per cent annually, then even with zero pure time preference, the annual discount rate applied to future consumption would be 1.5 per cent (using $\theta = 1.5$).

The tradition of social CBA discounts future consumption effects by the SRTP. However, it also allows for a divergence between the rate of return on capital and the SRTP. This tradition thus requires that all capital (e.g. investment) effects be converted (i.e. expanded) into consumption-equivalents by applying a ‘shadow price of capital’, before discounting all consumption-equivalent values. On a basis of the literature, Cline (1992, 270–4) suggests a typical shadow price of capital of 1.6, so

⁷ See Arrow (1966); Feldstein (1970); Arrow and Kurz (1970); Bradford (1975).

that a unit of investment translates into 1.6 units of consumption.

In the 1995 report of Working Group III of the IPCC (Bruce, Lee and Haites 1996), a panel of experts referred to the discounting method just reviewed as the ‘prescriptive’ approach (Arrow *et al.* 1996). It contrasted this method with the ‘descriptive approach’ based on observed market rates of return. The discounting method used by Nordhaus and Boyer (2000) is a good example of the latter. They apply a Ramsey-type optimal-growth model in which they employ a rate of pure time preference set at 3 per cent, based on observed capital market rates.⁸ They take account of falling marginal utility by applying this discount rate to ‘utility’ rather than directly to consumption. Their utility function is logarithmic ($U = \ln c$, where U is *per capita* utility and c is *per capita* consumption). In this utility function, the absolute value of the elasticity of marginal utility is unity ($\theta = 1$). If *per capita* consumption grows systematically at 1 per cent, their overall discount rate is thus equivalent to about 4 per cent annually (3 per cent pure time preference plus 1 per cent from logarithmic utility). At this rate, \$100 in damages 200 years from today shrinks to 0.04 cents in today’s values. It would take savings of about \$2,500 in avoided damages 200 years from today to warrant giving up just \$1 in consumption today, at this rate. I continue to believe that this type of discounting, whether descriptive or not, trivialises the problem of global warming by introducing a severe bias against counting the damage experienced by future generations.⁹

A final conceptual issue in discounting using zero pure time preference involves implications for optimal saving and investment. Critics of the social cost-benefit approach sometimes argue that it must be wrong, because it would imply the need for a massive increase in saving and investment in order to drive the rate of return to capital down to the SRTP. Otherwise the economy would be sub-optimal. A variant on this argument is simply that instead of investing in greenhouse abatement, society should invest more in other goods and services generally and thereby more effectively keep the future generations no worse off by compensating their environmental damages with additional goods and services.

The answer to the first variant of this argument is that public policy should be second-best when it cannot be first-best. It has proven extremely difficult to boost private saving and investment rates. So even though it might be socially optimal to do so, if in fact that is impossible, that reality should not be allowed to prevent action on global warming. It might be first-best to raise saving and investment simultaneously with adopting greenhouse abatement, but even in the absence of a boost to saving and investment it could be second-best to proceed with the greenhouse abatement.

The answer to the second variant of the capital argument, which I have called the ‘Fund for Greenhouse Victims’ approach, is that it is implausible (Cline, 1992, 265). Suppose that society could devote 1 per cent of GDP to reducing global warming, but instead chooses to invest this amount to compensate future generations for unabated warming. Even if the corresponding tax revenues and investments could be mobilised, this approach would not be credible. The extra capital assets thereby obtained would have life spans of 10–15 years, whereas the life span of the carbon abatement benefit is on the scale of two centuries. The beneficiaries of additional investments in schooling today would be today’s youth, not the youth of two centuries from now. Moreover, if somehow additional goods and services for the future generations could be assured, those generations could easily place a much lower valuation on them than would be required to compensate them for the environmental damages.

Measuring Benefits

From the outset of economic analysis of global warming more than two decades ago, there has

⁸ As discussed below, they allow for a slight decline in the rate of pure time preference over time.

⁹ The dichotomy of ‘descriptive’ and ‘prescriptive’ is misleading, as it could be interpreted as implying that the former matches reality while the latter is based solely on theory. Yet it is quite ‘descriptive’, in terms of according with observed data, to argue that the rate of pure time preference is zero. It turns out that the real rate of return on US treasury bills – the only risk-free instrument (including freedom from risk of change in the interest rate) at which households can transfer consumption over time – has historically been about zero.

been far more empirical work on the side of calculating the cost of abatement than on the side of measuring the potential 'benefits' from *climate damage avoided*. Quantifying the potential damages is simply a far more elusive task. On the basis of then-available estimates by the US Environmental Protection Agency and other sources, Cline (1992) compiled benchmark estimates for damage that could be expected from warming associated with a doubling of CO₂. This damage turned out to be an aggregate of about 1 per cent of GDP (1992, 131). The largest damage was in agriculture (about one-quarter of the total damage); increases of electricity requirements for cooling in excess of reductions for heating (about one-sixth of the total); sea-level rise, adverse impact of warming on water supply and loss of human life from heat waves (each about one-tenth of the total); and forest loss and increased tropospheric ozone pollution (each about one-twentieth of the total). The estimate included a speculative and probably lower-bound number for species loss. Other potential losses (human amenity, human morbidity, other pollution effects of warming) were recognized but omitted from quantification.

The 1 per cent of GDP benchmark was about the same as suggested by Nordhaus (1991) who, however, specifically calculated only agricultural losses (far smaller) and sea level damages (somewhat larger) and arbitrarily assumed 0.75 per cent of GDP as a comfortable allowance for all other losses not specifically examined. Two other analyses quantifying broadly the same categories as in Cline (1992) reached similar magnitudes for the USA (Fankhauser 1995, at 1.3 per cent of GDP, and Tol 1995, at 1.5 per cent of GDP) and in addition extended the estimates to other parts of the world. A higher estimate of 2.5 per cent of GDP damage was obtained by Titus (1992), who however applied a higher $2 \times \text{CO}_2$ warming assumption (4°C) than in the other studies (2.5°C). The Fankhauser and Tol studies obtained modestly higher damage estimates for non-OECD countries (1.6 per cent and 2.7 per cent of GDP, respectively).¹⁰

Cline (1992) also suggested benchmark damage for very-long-term warming with a central value of

6 per cent of GDP for warming of 10°C, on the basis of plausible non-linear relationships of damage to warming in each of the damage categories. This implied an average exponent of 1.3 for relating the ratio of damage to the ratio of warming (i.e. $6/1 = [10/2.5]^{1.3}$).

Subsequent damage estimates have tended to suggest somewhat lower magnitudes for $2 \times \text{CO}_2$ damage for the USA, but there has tended to be greater emphasis on the potential for larger damages in developing countries, in part because of lesser scope for adaptation. A 'Ricardian' model relating US land values to temperatures estimated by Mendelsohn, Nordhaus and Shaw (1994) suggested that a modest amount of warming might have positive rather than negative effects for US agriculture, but Cline (1996) suggested that this result was vulnerable to an overly optimistic implicit assumption about the availability of irrigation water.

Incorporating Risk of Catastrophe

A third issue that warrants emphasis is the question of catastrophic impacts. The most well known is that of the shut-down of thermohaline circulation in the Atlantic ocean. There is a 'conveyor belt' that involves the sinking of cold water near the Arctic and upwelling of warm water in the Southern Atlantic, giving rise to the Gulf Stream which keeps northern Europe warm. Increased melting of polar ice could reduce the salinity and specific gravity of the cold water entering the ocean there, possibly shutting down the ocean conveyor belt. The approach to this and other catastrophic risks in Cline (1992) is merely to treat them as additional reasons to act above and beyond the basic economic attractiveness of greenhouse abatement as evaluated in a CBA. The analysis of that study does incorporate risk in a milder form, however, by placing greater weight on upper-bound scenarios and (non-catastrophic) damage coefficients than on lower-bound combinations in arriving at an overall weighted BCR for action.

Nordhaus and Boyer (2000) make an important contribution in attempting instead to incorporate catastrophic risk directly into the CBA. On the basis of a survey of scientists and economists working in the area of global warming, they first identify a range of potential damage and associated

¹⁰ For a survey of damage estimates, see Pearce *et al.* (1996).

probabilities of catastrophic outcomes. After some upward adjustment for 'growing concerns' in scientific circles about such effects (2000, 88), they arrive at estimates such as the following. The expected loss in the event of a catastrophe ranges from 22 per cent of GDP in the USA to 44 per cent for OECD Europe and India (2000, 90). The probability of a catastrophic outcome is placed at 1.2 per cent for 2.5°C warming and at 6.8 per cent for 6°C warming (the highest they consider). Using a 'rate of relative risk aversion' of 4, they then calculate that these probabilities and damages translate into a willingness-to-pay to avoid catastrophe of 0.45 per cent of GDP in the USA at 2.5°C and 2.53 per cent of GDP at 6°C, while the corresponding magnitudes are 1.9 per cent and 10.8 per cent of GDP, respectively, for both OECD Europe and India. The higher estimates for Europe reflect greater vulnerability (in particular because of the risk to thermohaline circulation). Other regions are intermediate.

Nordhaus and Boyer (2000) then directly incorporate this 'willingness-to-pay' directly into their damage function relating expected damage to warming. The result is a highly non-linear function, in which damage as per cent of GDP is initially negative (i.e. beneficial effects) up to 1.25°C warming, but then rises to 1.1 per cent of GDP for 2.5°C warming, 1.6 per cent of GDP for 2.9°C, 5.1 per cent of GDP for 4.5°C and 10 per cent of GDP for 6°C warming.¹¹ Although their direct incorporation of catastrophic risk is heroic, it surely captures the public's true concern about the possible scope of global warming damage more effectively than do the usual central estimates of benchmark $2 \times \text{CO}_2$ damage at 1 per cent of GDP or so.

Adaptation

This chapter examines the policy option of abatement of emissions contributing to global warming. A natural question is whether instead there could be an alternative policy of adaptation to climate change. In practice, adaptation turns into more of an inevitable concomitant of global warming rather than a viable stand-alone policy. The amelioration of climate damages feasible through adaptation tends to be already incorporated in the estimates of baseline damage, which in effect are 'damage

net of costs and benefits of feasible adaptation'. Specifically, in the Nordhaus–Boyer damage estimates to be used in the present study, key components already take account of adaptation. Their relatively low damage estimates for agriculture and some other sectors are premised on incorporating net effects of adaptation.¹²

Carbon Taxes versus Quotas with Trading

The analysis of this chapter examines optimal carbon taxes in the light of potential reductions in climate damage through abatement. In principle, any optimal path for emissions and carbon taxes can also be translated into an equivalent path for global carbon quotas coupled with free market trading of these quotas. The market price of the quotas should wind up being the same as the carbon tax that generates the emissions path targeted. Countries receiving an abundant quota would tend to find their value in international trading would exceed the value in their domestic use and would tend to 'export' (sell) the quotas, while countries receiving relatively scant quotas in view of their energy–economic base would tend to 'import' (buy) them. There are several key practical differences, however. Perhaps the most important is that a regime of quotas would presume some form of allocation that would be unlikely to have the same distributional effects as a carbon-tax approach. In particular, quota allocations based substantially on population rather than existing total energy use would tend to redistribute quota 'rents' to large countries with low *per capita* income (India, China), whereas the carbon-tax approach would essentially distribute the quota-equivalents on a basis of existing economic strength and hence capability to pay the tax.

A second important difference has to do with the degree of certainty about the response of

¹¹ In the DICE99XL version of their model, the damage function (per cent of GDP) is: $d = 100 \times (-0.0045T + 0.0035T^2)$, where T is the amount of warming (°C) above 1990.

¹² Thus, Nordhaus and Boyer (2000, 70) state: 'many of the earliest estimates (particularly those for agriculture, sea-level rise, and energy) were extremely pessimistic about the economic impacts, whereas more recent studies, which include adaptation, do not paint such a gloomy picture'.

carbon-based energy supply and demand to prices. When pollution has sharply rising marginal damages, and supply–demand price elasticities are highly uncertain, set quotas (which are then traded) can be a better approach than taxes. When the marginal pollution damages are relatively constant but marginal abatement costs are steep, taxes can be a preferable approach in order to avoid excessive cost of overly ambitious emissions targets (Weitzman 1974). In practice, however, global warming policy has such a long time horizon that either a tax-based or a quota-based approach would seem capable of periodic review and adjustment.

Previous Cost-Benefit Analyses

In part because of the difficulty of measuring potential global warming damage, and hence the economic benefits of abatement, there are relatively few cost-benefit studies, whereas there are numerous estimates of costs of specified abatement programme. This section will highlight two principal previous studies: Cline (1992) and Nordhaus and Boyer (2000).¹³

Cline 1992

My study in 1992 examined a three-century horizon involving much higher future atmospheric concentration of greenhouse gases than had previously been considered. This was based in part on the analysis by Sundquist (1990), indicating that over this time span the atmospheric concentration of CO₂ alone could rise to 1,600 ppm, far above the usual benchmark of doubling to 560 ppm. Based on then existing projections of emissions through 2100 (Nordhaus and Yohe 1983; Reilly *et al.* 1987; Manne and Richels 1990), I calculated a baseline of global carbon emissions rising from 5.6 GtC in 1990 to a range of 15–27 GtC in 2100. Thereafter the baseline decelerated to about 0.5 per cent annual growth, but even at the slower rate reached

an average of about 50 GtC annually in the second half of the twenty-third century (Cline 1992, 52, 290). These projections were based on the view that there was abundant carbon available at relatively low cost, primarily from coal resources, to generate from 7,000–14,000 GtC cumulative emissions (Cline 1992, 45, based on Edmonds and Reilly 1985, 160), so that rising resource costs could not be counted upon to provide a natural choking-off of emissions by the market. Assuming atmospheric retention of one-half of emissions, and taking into account other greenhouse gases, I calculated realized warming of 4.2°C by 2100 and ‘committed’ warming of 5.2°C by that date under business-as-usual (non-abatement). For the very long term, I estimated 10°C as the central value for warming by 2300, using a CS of 2.5°C. I placed upper-bound warming (for CS = 4.5°C) at 18°C. As discussed above, the corresponding damage amounted to about 1 per cent of GDP for the central value by about 2050 (the estimated time of realized warming from CO₂ doubling above pre-industrial levels already by 2025), rising to a central estimate of 6 per cent of GDP by 2300 and, in the high-CS case, 16 per cent of GDP by 2275 (1992, 280).

On the side of abatement costs, several ‘top-down’ modelling studies then available provided estimates, which tended to cluster in the range of about 1–2 per cent of GDP as the cost of cutting carbon emissions from baseline by 50 per cent in the period 2025–50, and about 2.5 to 3.5 per cent of GDP as the cost of reducing emissions from baseline by about 70 per cent by 2075–2100 (Cline 1992, 184). One study in particular (Manne and Richels, 1990) suggested that by the latter period there would be non-carbon ‘backstop’ technologies that could provide a horizontal cost-curve of abundantly available alternative energy at a constant cost of \$250 per ton of carbon avoided. For comparison, \$100 per ton of carbon would equate to \$60 per ton of coal (about 75 per cent of current market prices), \$13 per barrel of oil, and 30 cents per gallon of gasoline.

Another family of studies in the ‘bottom-up’ engineering tradition suggested that there was at least an initial tranche of low-cost options for curbing emissions by moving to the frontier of already available technology in such areas as building standards

¹³ The Working Group III review for the IPCC in 1995 identified only two other CBAs then available, and only one of them (Peck and Teisberg 1992) was published (Pearce *et al.* 1996, 215).

and higher fuel efficiency standards for vehicles. In addition, numerous studies suggested low-cost carbon sequestration opportunities from afforestation, which could, however, provide only a one-time absorption of carbon in the phase of forest expansion. Taking these initial lower-cost options into account, I estimated that world emissions could be cut by about one-third for as little as 0.1 per cent of world product in the first two decades; but that by about 2050 it would cost about 2 per cent of world product to cut emissions 50 per cent from the baseline. By late in the twenty-first century emissions could be reduced by up to 80 per cent from the baseline for still about 2 per cent of GDP in abatement costs, because of the widening of technological alternatives (Cline 1992, 231–2).

As discussed above, because of the later arrival of climate damage and the earlier dating of abatement measures, the discount rate is central to arriving at a CBA. Cline (1992) applies the SRTP method with zero pure time preference and conversion of capital effects to consumption equivalents, as summarized above. The study analysed a global policy of reducing emissions to 4 GtC and freezing them at that level. In the base case, the present value of benefits of damage avoided were only three-quarters as large as the present value of abatement costs. However, an examination of a total of thirty-six alternative cases showed that in several combinations of high damage ($CS = 4.5^{\circ}C$, and/or damage exponent = 2 rather than 1.3, and/or base damage = 2 per cent of GDP rather than 1 per cent in light of unquantified effects) the BCR could reach well above unity. To arrive at an overall evaluation, and to give some weight to risk aversion, the analysis placed 1/2 weight on the base case, 3/8 weight on the upper-bound damage outcome and 1/8 weight on the lower-bound damage outcome. The result was a weighted BCR of 1.26 for reducing global emissions to 4 GtC annually and holding them to this ceiling permanently in the future (1992, 300).

Nordhaus' DICE Model

In a body of work spanning more than two decades, William Nordhaus has provided successive estimates of optimal carbon abatement (Nordhaus

1991, 1994; Nordhaus and Boyer 2000). His results have systematically found that while optimal abatement is not zero, neither is it very large. The most recent analysis (Nordhaus and Boyer 2000) finds that the optimal reduction in global carbon emissions is only 5 per cent at present, rising to only 11 per cent from the baseline by 2100. Correspondingly, the optimal carbon tax is only \$9 per ton by 2005, rising to \$67 by 2100 (2000, 133–5). Optimal policy reduces warming by 2100 by a razor-thin $0.09^{\circ}C$, or from the baseline $2.53^{\circ}C$ to $2.44^{\circ}C$ (2000, 141). Although this change is for all practical purposes negligible, the authors apparently judge that it will be sufficient to successfully 'thread the needle between a ruinously expensive climate-change policy that today's citizens will find intolerable and a myopic do-nothing policy that the future will curse us for' (2000, 7).

I have previously shown that the earlier version of the DICE model could generate far higher optimal cutbacks and optimal carbon taxes if pure time preference is set at zero in my preferred SRTP method (Cline 1997). However, the DICE model is an attractive vehicle for integrated climate–economic analysis. In particular, it provides a basis for identifying an optimal time path for emissions and abatement, whereas the 4GtC ceiling experiment in Cline (1992) constitutes a single imposed policy target. Nordhaus has also made the model available for use by other researchers. The approach of this chapter is to use the model as a basis for evaluating alternative policy strategies, but only after making adjustments in certain key assumptions and, in some cases, calibrations. The change in the discounting methodology is the most important.

Before discussing the changes made to the model, however, it is useful to obtain a feel for the structure of DICE. The model begins with baseline projections of population, *per capita* consumption, carbon emissions and emissions of non-carbon greenhouse gases. Global output is a function of labour (population) and capital, which rises from cumulative saving. A climate damage function reduces actual output from potential as a function of warming. In the climate module, emissions translate into atmospheric concentrations and hence radiative forcing. Concentrations are increased by emissions but reduced by transit of CO_2 from the atmosphere to the

upper and, ultimately, lower oceans, in a ‘three-box’ model. Warming is a function of radiative forcing, but also a (negative) function of the difference between surface and low-ocean temperature. This means that the ocean thermal lag between the date of committed and realized warming stretches out substantially as the CS parameter is increased, as discussed below.

There is a cost function for reduction of emissions from the baseline. This function is relatively low-cost at moderate cutbacks. Thus, in the Excel version of the most recent version of the model (hereafter referred to as DICE99NB), as of 2045 it would cost only 0.03 per cent of gross world product (GWP) to cut emissions from the baseline by 10 per cent; only 0.32 per cent of GWP to cut emissions by 30 per cent; and only 0.97 per cent to cut them by 50 per cent. Costs then begin to escalate, however, and it would cost 2.3 per cent of GWP to cut emissions by 75 per cent at that date.¹⁴

The model is optimized by a search method applying iterative alternative values of the ‘control rate’ (percentage cut of emissions from the baseline) and evaluating a social welfare function each time. Welfare is the discounted present value of future utility, and the utility function is logarithmic (as discussed above). The optimal carbon abatement path is that which maximizes welfare after taking account of both abatement costs and the opportunity for higher actual output as a consequence of lesser climate damage.¹⁵ The nearly *de minimis*

cost of reducing emissions by 10 per cent, combined with the Nordhaus–Boyer conclusion that optimal cuts are below 10 per cent for most of this century, shows immediately that the driving force behind the minimal-action conclusion is not an assumption that it is costly to abate, but instead a calculation that there is very little value obtained in doing so. The minimal value of abatement benefits is in turn driven mainly by the discounting method.

Adapting the DICE99 Model

This study uses the Nordhaus–Boyer DICE99 model,¹⁶ designated as DICE99NB. The preferred version in this study applies several modifications to obtain what will be called the DICE99CL model. The appendix sets out details on these modifications. This section sets out the reasons for the most important changes.

Rate of Pure Time Preference

For the reasons set out above, the preferred value for pure time preference (ρ above) is zero. The most direct way to show the importance of this parameter is to consider the results of DICE99NB when there are no other changes except for setting pure time preference at zero. In the Nordhaus–Boyer (NB) version, this rate begins at 3 per cent, and slowly falls over time (to 2.57 per cent by 2055, 2.26 per cent by 2105 and 1.54 per cent by 2155). Figures 1.1 and 1.2 show the optimal abatement profiles (carbon tax and percentage cut from the baseline) using DICE99NB with the original pure time preference and zero pure time preference, respectively. As shown, far more aggressive action is found optimal when pure time preference is set to zero. Thus, whereas by 2055 in the original version the optimal carbon tax is \$33, when pure time preference is zero the optimal tax is \$240 at that date. Optimal per cent cuts in emissions from baseline are in the range of 50 per cent through most of the twentieth century when pure time preference is zero, instead of 5 to 10 per cent as in the original case with 3 per cent pure time preference.¹⁷

Figures 1.1 and 1.2 refer to optimization of the DICE model with respect to the carbon tax

¹⁴ This and other specific calculations using the model are obtained using the Excel spreadsheet version of DICE99 available at <http://www.econ.yale.edu/~nordhaus/homepage/dicemodels.htm>.

¹⁵ Full optimisation of the model allows the savings rate to vary, as well as the carbon abatement rate.

¹⁶ A more thorough analysis could be carried out by adapting the regional NB model, RICE, along the lines done here for the globally aggregate DICE99 model. This more extensive task was beyond the scope of the present chapter.

¹⁷ The downward slope in the optimal cut curve in the case of zero time preference is probably exaggerated by the anomaly of a rising linear component of the abatement cost function, as discussed below. The Excel version of the cost curve to approximate the RICE results is meant to provide a close approximation only through 2100 and close to the optimal cut ranges identified in Nordhaus and Boyer (2000).

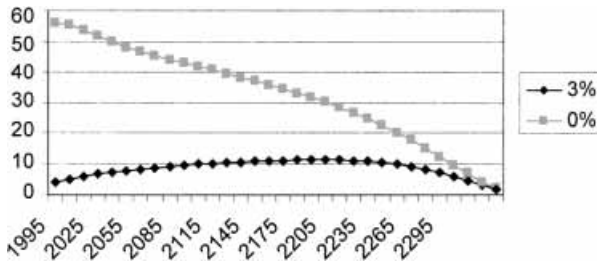


Figure 1.1. *DICE99NB optimal % cut from baseline at alternative pure time preference rates*

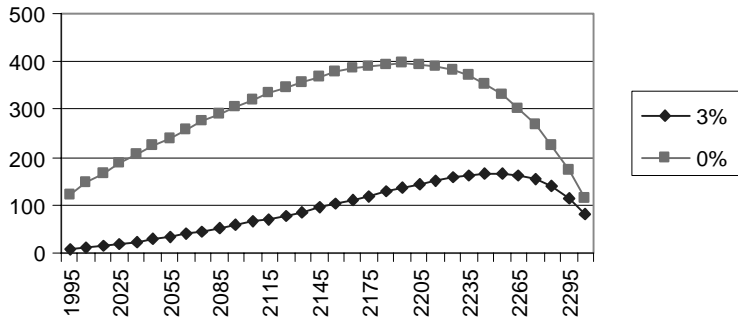


Figure 1.2. *DICE99NB optimal carbon taxes at alternative pure time preference rates*

only. If in addition the savings rate is allowed to be optimized, then in the variant with zero pure time preference the optimal control rates and carbon taxes are slightly higher, and the savings rate is far higher (averaging 33 per cent over the twenty-first century rather than 23 per cent as in the baseline).¹⁸ However, as discussed above, ‘full optimization’ including a major boost to the savings rate, is not realistic. The analyses that follow optimize only the carbon tax and treat the savings rate as exogenous.

Discounting Future Consumption

As discussed above, the social cost-benefit approach uses the SRTP to discount future consumption. The adapted model does this directly, using an elasticity of marginal utility (θ) of 1.5 (absolute value) and identifying a cumulative *per capita* consumption growth rate (g) that is specific to each of the periods (decades) in the model. In this approach, there is no need further to shrink rising

consumption by translating it into ‘utility’ through a logarithmic function (see the appendix).

Shadow-Pricing Capital

The SRTP method also requires conversion of all capital effects into consumption-equivalents. In practice, this principally involves an expansion of the abatement cost function to take account of the fact that a portion of the resources withdrawn to carry out abatement would come out of investment rather than consumption.

Baseline Carbon Emissions

Even though the more recent Nordhaus and Boyer (2000) study incorporates a higher climate damage function than in Nordhaus (1994), it arrives at about

¹⁸ For example, in 2195 the optimal carbon tax is 44 per cent instead of 41 per cent with full optimization, and the carbon tax is \$353 per ton instead of \$320, for the zero pure time preference variant.

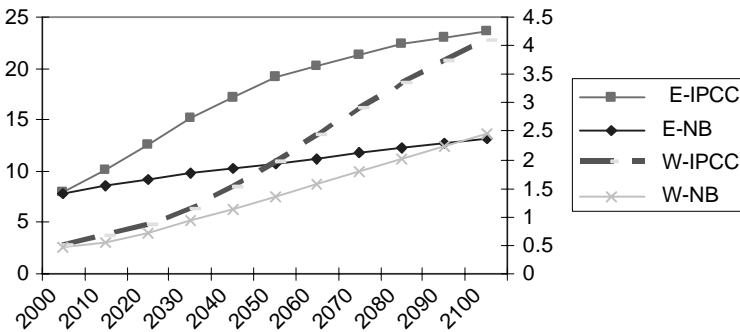


Figure 1.3. Carbon emissions (left, GtC) and warming (right, °C)

the same amount of optimal abatement. The main reason is that baseline emissions are scaled back in the later study, so there is less to cut back. Whereas global output by 2100 is set 13 per cent lower than before, with population 8.5 per cent higher (at 10.7 billion) but output per person 20 per cent lower (at \$9,100 in 1990 prices), carbon emissions are 48 per cent lower than before (at only 12.9 GtC, down from 24.9 GtC; 2000, 5). The drop in carbon intensity (from 0.22 tons per \$1,000 of GDP in the earlier study to only 0.13 tons) stems mainly from the authors' new view on a steeply rising cost curve for fossil fuel extraction after a cumulative 6,000 GtC carbon-equivalent has been used.

The basis for the sharp reduction in projected carbon intensity of output is not clear, however. In particular, with annual emissions averaging about 10 GtC in the twenty-first century, the new Nordhaus–Boyer baseline would exhaust only about one-sixth of the 6,000 GtC cumulative amount available before the sharp increase in extraction costs. As suggested above, my preferred baseline for emissions is still the path used in Cline (1992), which is also relatively close to the average of three of the four 'A' series in the IPCC 2001 report: A1B, A1F1 and A2 (table 1.1).¹⁹ The other

scenarios tend to be inconsistent as 'business-as-usual' baselines, because they presume sharp drops in carbon intensity without any special economic incentive to prompt the corresponding technological change, in the absence of any carbon tax.

Figure 1.3 shows the contrast between the 3As emissions baseline from the IPCC and the much lower Nordhaus–Boyer baseline. In the IPCC average, emissions reach about 24 GtC in 2100 (the same as in Nordhaus 1994) whereas in the new Nordhaus–Boyer baseline they reach only 13 GtC. Figure 5.3 also shows the average projected baseline warming above 1990 for the 3As scenarios from the IPCC. By 2100, realized warming in the three IPCC scenarios averages 4.1°C. This is virtually the same as in Cline (1992), as discussed above, but is far above the 2.45°C in Nordhaus–Boyer. A major adaptation to the model, then, is to replace the emissions baseline, restoring it to a path much more like Nordhaus' previous projections. Further details on changes in the emissions and world output baselines are discussed in the appendix.

Other Adaptations

As discussed in the appendix, the climate module of DICE99NB generates a surprisingly low rate of atmospheric retention of emissions over the period of the first century, so in addition to a low emissions baseline there is an even lower build-up in atmospheric stock. The projections in IPCC (2001) provide a basis for relating atmospheric retention to emissions over this period, and this

¹⁹ Note that other leading analysts of carbon emissions scenarios do not appear to have adopted drastic reductions like those of Nordhaus and Boyer. For example, Manne and Richels (2001) still apply a baseline that places global emissions at 21 GtC in 2100, down only moderately from their earlier projection of 26.9 GtC by 2100 (Manne and Richels 1991) and far above the new Nordhaus–Boyer level.

relationship is used as the basis for the adaptation of the model. This involves relatively modest alterations in the rates of transfer of CO₂ between the various 'boxes' of the three-box model, as discussed in the appendix.

Abatement Cost Function

Finally, a modification is made to the abatement cost function for the period after 2100. The Excel version of DICE99 has the seeming anomaly of a rising trend over time for the linear term in the abatement cost function, whereas it is usually judged that for any target percentage cut from the baseline, the economic cost (as a percentage of GDP) should fall over time thanks to the widening array of technological alternatives. Indeed, in the GAMS version of the DICE model, this term does fall over time. The use instead of a rising linear term in the Excel version reflects the need to make its optimization results track those of the more regionally detailed RICE model. Because the latter can take advantage of initial low-cost carbon abatement in developing and transition economy regions (for example), at the global level the gradual exhaustion of this opportunity is mimicked by having a rising rather than falling linear term for the abatement cost function. Although the result is successfully to track the optimal results of RICE for the first 100 years, Nordhaus has indicated that this cost function may not track well for the more distant future.²⁰

The modification made here is to place a ceiling on the linear term in the abatement cost function, freezing it at its 2100 level for all later periods. This means that it does not reflect the falling-cost opportunities of a widening technological menu, but neither does it project rising cost of abatement. This approach implicitly makes the reasonable assumption that the process of exhausting the regional 'easy pickings' is complete by 2100.

Warming Baseline

The result of these changes to arrive at the adapted model, DICE99CL, is a substantially higher baseline for warming. In the NB baseline, warming reaches 2.5°C by 2100, 3.8°C by 2200 and 4.5°C by 2300. In the adapted (CL) baseline, warming

reaches 3.3°C by 2100, 5.5°C by 2200 and 7.3°C by 2300. While this is a more pessimistic projection than in the NB outlook, it is somewhat more optimistic than that of the three A-series scenarios of the IPCC (2001a) discussed above, which on average place warming by 2100 (above 1990) at 3.7°C (figure 1.3).

The DICE99CL baseline warming for the very long term (2300) is lower, at 7.3°C, than that in Cline (1992), at 10°C. The difference is attributable to the lower assumption in the model used here about the impact of non-carbon greenhouse gases. DICE99CL adopts the NB assumption that radiative forcing from non-carbon gases hits a ceiling of 1.15 wm^{-2} in 2100 and stays fixed at that rate thereafter. In contrast, Cline (1992, 53) assumed that the *ratio* of non-carbon to carbon radiative force remained constant after 2100 at its level projected by the earlier IPCC studies for that time (with a ratio of 1.4 for total to carbon radiative forcing). IPCC (2001a) did not project radiative forcing beyond 2100, but it did state that carbon dioxide would comprise a rising fraction of total radiative forcing during the course of the twenty-first century, a view potentially consistent with little increase in non-carbon radiative forcing after 2100. The overall effect is to place total radiative forcing by 2300 at 13.6 wm^{-2} , in contrast to the level of 17.5 wm^{-2} which it would reach if non-carbon radiative forcing remained proportional to carbon forcing at its 2100 ratio. In this important dimension, the adapted model here (DICE99CL) is considerably less pessimistic about the extent of very-long-term warming than was my original study (Cline 1992). From this standpoint, optimal abatement estimates may be on the low side, as the assumption that non-carbon radiative forcing does not rise after 2100 may be too optimistic.

²⁰ Personal communication, 8 January 2003. Note also that for the first century the Excel version of the DICE99 cost function generates abatement cost estimates that are comparable to those of other leading energy-economic models. Thus, in an OECD exercise implemented with three such models, the average cost of cutting emissions from baseline by 45 per cent in 2020 was 2.1 per cent of GWP; by 70 per cent in 2050, 2.9 per cent; and by 88 per cent in 2095, 4.7 per cent (Hourcade *et al.* 1996, 336; Edmunds and Barns 1992; Manne 1992; Rutherford 1992). The corresponding cost estimates using the DICE99 Excel function are 0.7, 2.1 and 4.3 per cent, respectively.

Policy Strategy 1: Optimal Carbon Tax

With the adapted model (DICE99CL) in hand, it is possible to apply it to examine key policy strategies for dealing with global warming. The first general policy would be for the international community to agree that all countries would levy carbon taxes. The rate for the taxes would be coordinated internationally, but each country would collect the tax on its own emissions and use the revenue for its own purposes. An attractive feature of this approach is that it could provide substantial tax revenue to national governments. In many countries, weak fiscal revenue performance has been at the root of serious macroeconomic breakdowns. A substantial source of new revenue could thus have favourable macroeconomic effects in many countries.

Figure 1.4 shows the path of the optimal carbon tax and optimal percentage cutback in carbon emissions from the business-as-usual baseline, using the adapted DICE99CL model. The optimal abatement strategy turns out to be relatively aggressive. Emissions would be cut from baseline by about 35–40 per cent early on, by nearly 50 per cent by 2100 and by a peak of 63 per cent by 2200. The corresponding carbon taxes would start out at \$128 per ton, and then rise to \$170 by 2005, \$246 by 2025 and \$367 by 2055, eventually reaching \$1,300 in 2200 before tapering off. The higher baseline for emissions and warming mean that potential climate damage is greater than projected by NB, so the optimal cutbacks and carbon taxes are much higher than would be obtained in DICE99NB if the only change to their model were the enforcement of zero pure time preference (figures 1.1 and 1.2).

Table 1.2 reports the absolute levels of carbon emissions in the baselines and in the optimal cutbacks for three sets of studies: my 1992 study; the results of applying the DICE99NB model; and the adapted DICE99CL model. The baseline emissions are set in the DICE99CL model to be very close to those in Cline (1992), and are far above those in the DICE99NB baseline. In the first half of this century the optimal emissions in the DICE99CL model are intermediate between those in the NB optimal path and those of the Cline (1992) aggressive abatement path. Later in the horizon the absolute levels of emissions in the CL model begin to equal, and eventually exceed, those in the NB optimal path, but only because the CL baseline is so much higher than the NB baseline (so that the CL optimal path ends up being higher despite larger per cent cuts from baseline).

Figure 1.5 shows the amount of warming above 1990 for the CL baseline and for the optimal abatement. Whereas warming reaches 7.3°C by 2300 without action, under optimal abatement it is limited to 5.4°C – a level that is uncomfortably on the high rather than low side.

Figure 1.6 shows climate damage as a percentage of GWP in the base and optimal cases. The difference between the two curves represents the economic benefits of abatement. When these benefits are plotted in figure 1.7 against the abatement costs, both as a percentage of GWP, the characteristic timing asymmetry is strongly evident: abatement costs come earlier in the horizon, and benefits of damage avoided begin to exceed abatement costs only after several decades have passed. Even taking account of rising gross world product,

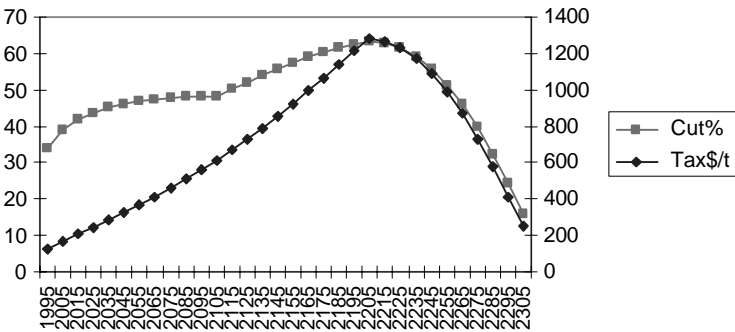


Figure 1.4. DICE99CL optimal cut (% left) and carbon tax (\$ right)

Table 1.2. Baseline and Optimal Carbon Emissions (GtC), 1995–2295

	1995	2005	2015	2025	2055	2095	2145	2195	2245	2295
Baseline										
Cline (1992)	6.7	6.9	9.4	10.9	13.8	21.6	28.9	39.2	49.4	63.3
DICE99NB	7.3	8.2	8.9	9.5	11	13	15.3	17.2	16.8	9.7
DICE99CL	7	8.6	10.1	11.6	15.8	21.4	29	38	49.8	62.8
Optimal										
Cline (1992)a	4	4	4	4	4	4	4	4	4	4
DICE99NB	7.3	7.8	8.4	8.9	10.1	11.3	13.7	15.3	15.2	9.5
DICE99CL	7.3	5.7	6.3	6.9	8.6	11.2	13.0	14.3	22.4	48.6

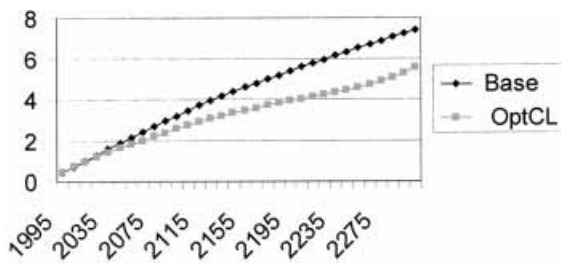


Figure 1.5. Baseline and optimal warming (°C)

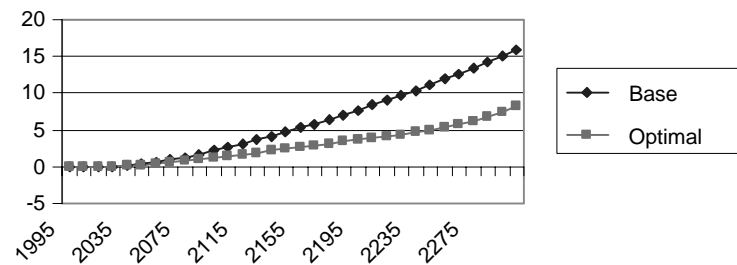


Figure 1.6. Climate damage as % of GWP

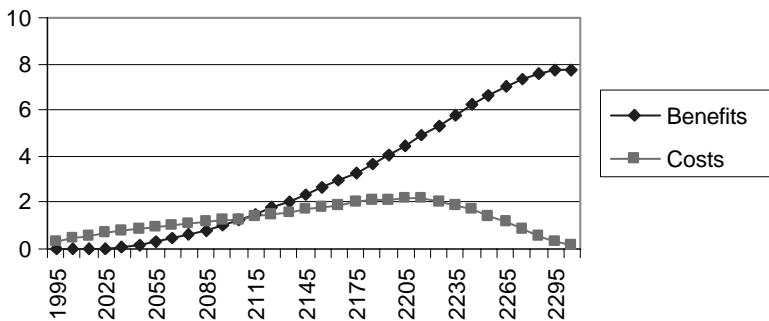


Figure 1.7. Benefits and costs of optimal abatement (% GWP)

it is easy to see from figure 1.7 that if effects after 2100 or so are essentially ignored by using a relatively high time discount rate, the level of abatement judged optimal when setting pure time preference at zero will be considered far too costly, demonstrating once again the centrality of the discounting methodology for policy analysis given the long time scales of this problem.

To recapitulate, the first policy strategy, economically optimal abatement, involves an aggressive programme that cuts global carbon emissions by an average of about 45 per cent from the baseline during this century and 55 per cent from baseline in the next century. This would require carbon taxes rising from about \$130–170 per ton through 2015 to about \$600 by 2100 and eventually \$1,300, before declining again. Using the discounting methodology set out above, and applying the percentage of GWP abatement costs and benefits of figure 5.7 to the projection of baseline GWP, this policy strategy would have abatement costs with a discounted present value of \$128 trillion (1990 prices) and benefits from avoided damage amounting to \$271 trillion. The BCR would thus be 2.1.

An implication of the result that the present value of benefits would be twice the present value of abatement costs is that there would be scope for more aggressive abatement that would still have positive net benefits, even though the ratio of benefits to costs would begin falling. That is, beyond the optimal amount of abatement, incremental benefits from damage avoided would begin to fall short of incremental costs.

An important specific instance of this point concerns the aggressive plan in Cline (1992): stabilization at 4 GtC. In a run of the DICE99CL model applying this ceiling, the climate effect of this stabilization is the limitation of warming to 3.2°C by 2300, compared to 7.3°C in the baseline and 5.4°C in the optimal abatement case. Abatement costs are considerably higher than in the optimal run here, reaching about 4 per cent of GWP by 2085 and reaching a plateau of about 5 per cent of GWP by 2205. (The cost estimate in Cline 1992, is instead a plateau of about 2.5 per cent of GWP by 2150 and

after: 1992, 280.) However, the DICE99CL estimates of benefits of the aggressive action plan (stabilization at 4 GtC) are also higher, as economic damage from warming is limited late in the horizon to a lower level (averaging about 1.5 per cent of GWP for the twenty-third century) than in the optimal path (averaging about 4.5 per cent of GWP through the twenty-third century but reaching 8 per cent by its end: figure 1.6). The discounted present value of benefits in the aggressive stabilization case amounts to \$435 trillion, and the present value of abatement costs, \$420 trillion, giving a BCR of 1.04. This is far lower than in the optimal case (figure 1.7, with a BCR of 2.1), but nonetheless shows net positive benefits. The more severe damage function in NB (2000) than in Cline (1992) is the reason why DICE99CL finds a (just barely) favourable BCR for the aggressive stabilization programme even though baseline warming in the very long term is lower at 7.3°C rather than the 10°C identified in Cline (1992).²¹

Policy Strategy 2: the Kyoto Protocol

The essence of the Kyoto Protocol (KP) is to have the industrial and transition economies cut emissions back to 5 per cent below 1990 levels and freeze them at that level, while allowing developing countries unlimited emissions. This strategy is inherently no more than second-best in at least two dimensions. First, it would seriously weaken prospective global abatement, given the probable large increase in developing country emissions. Second, despite the various vague provisions for ‘trading’ emissions (more fully among the ‘Annex I’ industrial countries but arguably between them and developing countries as well), the Kyoto structure inherently violates the least-cost solution of cutting emissions globally in a manner that equates the marginal cost of cutbacks across all countries.

Even so, it is possible that Kyoto is better than nothing, as it would contribute to at least some moderation of warming. The question is whether the benefits of this abatement would exceed the costs, taking account of the likely inefficiency of this strategy.

Nordhaus and Boyer (2000) find that the Kyoto targets have costs that exceed their benefits.

²¹ In the central case, the Cline (1992) damage function is less than quadratic with respect to warming, while the NB function is more than quadratic.

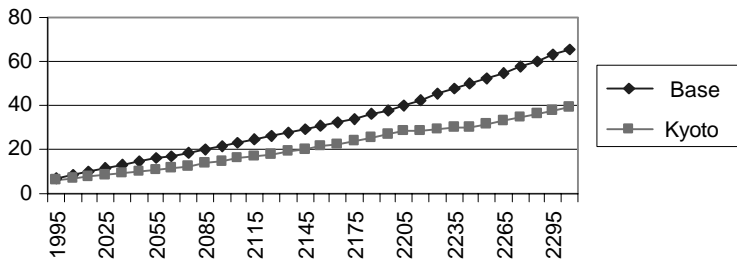


Figure 1.8. Global carbon emissions (GtC), baseline and Kyoto

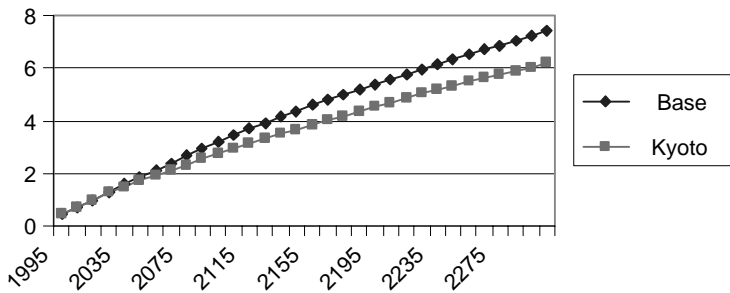


Figure 1.9. Baseline and Kyoto warming ($^{\circ}\text{C}$)

However, this finding is driven by two assumptions that are questioned in the present study. First, they assume a minimal increase in industrial country emissions in the baseline from present-day levels. As a result, in their projections Kyoto makes almost no difference to future global emissions. By 2105, baseline emissions are at only 13.25 GtC; with Kyoto, they are 12.8 GtC. Not surprisingly, Kyoto makes almost no difference to warming, and has minimal damage avoidance benefits. Second, they use a rate of pure time preference of 3 per cent.

Cline (1992, 337) provides a sharply different picture of future industrial country emissions. For industrial OECD plus Eastern Europe and the former Soviet Union, emissions (excluding from deforestation) rise from 4.0 GtC in 1990 to 10.6 GtC in 2100 and 24.4 GtC by 2250. So there is plenty to cut under Kyoto.²² Developing country emissions rise by even more, from 1.66 GtC in 1990 to 10 GtC in 2100 and 25.4 GtC in 2250, posing the main problem with Kyoto: it will fail to curb a massive build-up in emissions from developing countries.

It is possible to use the DICE99CL model as a point of departure for analysing costs and benefits of the KP. The first step is to obtain the KP baseline for global emissions. This is done by cutting the

controlled (Annex I) country emissions by 5 per cent below 1990 levels to 3.8 GtC and freezing them at this level, while projecting the baseline emissions just discussed for developing countries. The result is a significant cut in global emissions as the time horizon lengthens (figure 1.8), although far less of a cut than in the optimal strategy of the previous section. The emissions path and all of the rest of the KP analysis assume that all Annex I countries, including the USA, participate.

With the emissions path in hand, it is possible to apply the climate module of DICE99CL to obtain the corresponding warming. Similarly, the climate damage function of the model can be applied to obtain the corresponding damage as a per cent of world product. Figures 1.9 and 1.10 display the baseline and Kyoto paths for warming and climate damage. It is evident in figure 1.9 that Kyoto is disappointing as a strategy for limiting global warming, as it reduces warming by 2300 only from 7.3 $^{\circ}\text{C}$ to 6.1 $^{\circ}\text{C}$. Even so, because of the high degree of nonlinearity in the NB damage function, the result is to cut global

²² Note, however, that Manne and Richels (2001) project much lower baseline emissions by 2100 for the Annex I countries (6 GtC), combined with much larger emissions for developing countries (15 GtC), especially China.

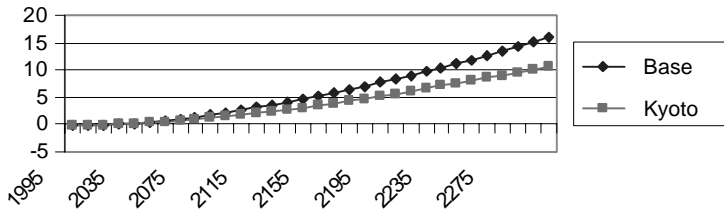


Figure 1.10. Climate damage as per cent of GWP, baseline and Kyoto

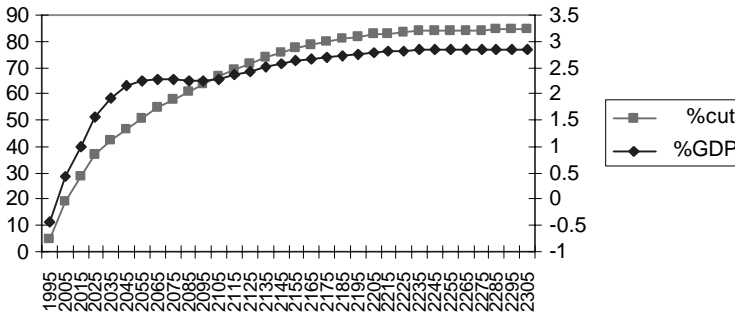


Figure 1.11. Kyoto: industrial country emission cuts (left) and cost (right)

climate damage by 2300 from 15.4 per cent of world product to 10.3 per cent.

What remains is to identify the abatement cost of the KP. This time, it is not appropriate to use the DICE99CL cost function, which is for global cuts. The core of the efficiency problem with Kyoto is that it does not take the lowest marginal cost cuts but instead imposes the cuts on a sub-set of the global economy: the industrial countries. Note that the issue here is in principle not one of *distribution* but *efficiency*. The same amount of total emissions could be obtained by lesser cuts in industrial countries, greater cuts in developing countries and transfers from industrial countries to compensate developing countries for the cuts made there.

The cost function, then, needs to be specified relative to the industrial countries. The mitigation cost survey in Hourcade *et al.* (1996) provides a basis for doing so. That study provides a summary

of twenty-nine studies with seventy-two emissions cut scenarios for the USA (1996, 304). Four studies show negative costs of emissions cuts. If these ‘bottom-up’ studies are omitted, the resulting point estimates provide a basis for regression estimates relating abatement cost as a percentage of GDP to the percentage cut in emissions from the baseline.²³ (This means that the summary regressions may tend to overstate rather than understate abatement costs, as they exclude the more optimistic bottom-up analyses.) These estimates confirm a falling cost over time for a given percentage cut from the baseline. Abatement cost estimates for Kyoto apply the 2020 regression for 2000–20 and the 2100 regression for all periods after 2100, and interpolate between the three benchmark regression years for all other periods. The resulting abatement costs as a percentage of industrial countries’ GDP, and percentage cut-backs in emissions from baseline for these countries, are shown in figure 1.11.

Because industrial countries’ GDP falls from 56 per cent of the world total (PPP basis) in 1995 to 36 per cent by 2100 and 28 per cent by 2300, the corresponding abatement costs as a percentage of world product are progressively smaller over time. Figure 1.12 shows the Kyoto abatement costs as a

²³ There are three regressions, one for each of three benchmark dates. For 2020, the result is: $z = -0.75 (-2.1) + 0.061 (6.8) C$; $\text{adj. } R^2 = 0.74$, where z is abatement cost as a percentage of GDP and C is the percentage cut in emissions from the baseline (t -statistics in parentheses). For 2050: $z = 0.63 (0.7) + 0.0332 (2.0) C$; $\text{adj. } R^2 = 0.16$. For 2100: $z = 0.11 (0.33) + 0.0325 (6.7) C$; $\text{adj. } R^2 = 0.73$.

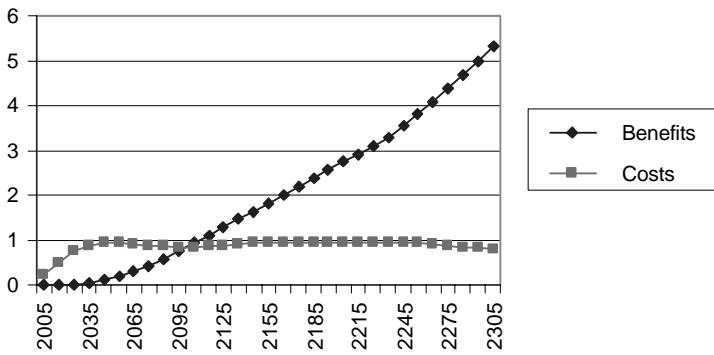


Figure 1.12. *Benefits and costs of Kyoto Protocol abatement (% world product)*

percentage of GWP, along with the benefits of Kyoto abatement as a percentage of world product. These benefits are simply the difference between baseline-warming climate damage and Kyoto-warming climate damage (from figure 1.10).

For the world as a whole, Kyoto abatement benefits overtake costs by 2100 and increasingly exceed them thereafter. It is the industrial countries who pay, however. Considering that their benefits as a percentage of GDP are the same curve as shown globally in figure 1.12, for the industrial countries Kyoto benefits overtake costs only by about 2200. On this basis, the resistance of some industrial countries to the Kyoto approach is understandable.

When the cost and benefit paths are applied to that for world product, and after augmenting the costs by a factor to adjust for shadow pricing of capital, and discounting using the SRTP method discussed above, the discounted present value of abatement benefits equals \$166 trillion (1990 prices) and the costs equal \$94 trillion, for a BCR of 1.77.²⁴ Somewhat contrary to the predominant view, then, the KP seems to pass a benefit-cost test globally, although it shows negative net benefits for the industrial countries. They enjoy a discounted present value of \$55 trillion, but pay the discounted present costs of \$94 trillion, so for their part alone they face a BCR of 0.58.

An important qualification to this estimate is that the benefit-cost calculus might be favourable for Europe as a sub-region within the industrial country group. Because the risk of thermohaline circulation shutdown poses the greatest potential damage to Europe, in their regional RICE model NB (2000,

160) find that Kyoto emissions ceilings would have a net positive benefit for Europe even in an arrangement in which emissions trading is allowed only within the OECD. This version has significant losses for the USA and for the world as a whole, however.

Quite apart from the unattractive cost-benefit calculation from the standpoint of industrial countries as a group, as noted the KP accomplishes relatively little in curbing warming. For the world as a whole, then, it is better than nothing, but not a persuasive answer to the problem of global warming. For industrial countries, its economic costs outweigh its economic benefits.

Policy Strategy 3: a Value-at-Risk Approach

In the 1990s, private financial firms have increasingly applied the approach of value-at-risk (VaR) in managing portfolio risk. Although the origins of this approach go back to Markowitz (1952), it was popularized by an influential study by a policy research group in the early 1990s (Group of Thirty 1993), and gained increasing attention because of the expansion of the derivatives market and the evolution of international bank regulation toward more sophisticated risk-related capital requirements for banks under rules developed by the Basel Committee.

²⁴ Abatement costs are multiplied by 1.13 to adjust for a shadow price applied to that portion of abatement resources that come out of saving rather than consumption.

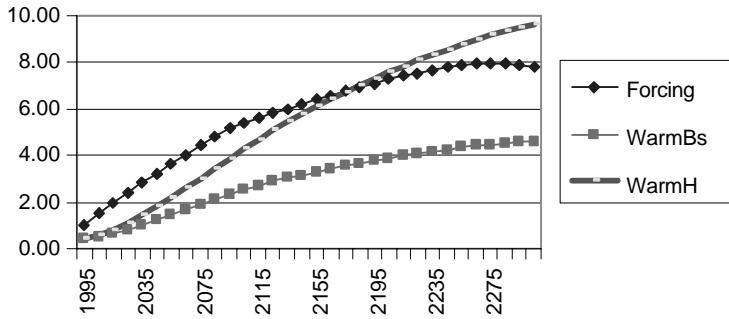


Figure 1.13. Radiative forcing (w/msq) and warming ($^{\circ}\text{C}$, NB baseline and 95% high)

The VaR approach identifies the maximum value that a firm can be expected to lose during a specified horizon and up to a specified probability. In the financial sector, horizons tend to be a day or a month. Target probability levels tend to be in the high ninety percentiles. The historical volatilities and covariances of individual assets in a portfolio are estimated to arrive at such probabilities. As applied to global warming, a VaR approach would focus on the prospective damage that could occur up to a fairly high level of probability that actual damage would be no greater than the estimated amount. Cost-benefit models in this area do not yet appear to have emphasized stochastic approaches with confidence intervals, but it could be that both the scientific and economic literature will evolve in this direction.

A potentially crucial recent study on the scientific side estimates the probability distribution of the CS parameter (Andronova and Schlesinger 2001). Using sixteen radiative forcing models capturing greenhouse gases, tropospheric ozone, anthropogenic sulphate aerosol, solar forcing and volcanos, the study uses Monte Carlo simulations to generate alternative temperature histories over the past 140 years. On this basis, it identifies probability distributions for CS. The study finds that the 90 per cent confidence interval for CS is between 1.0°C at the lower end and 9.3°C at the upper end. This means that to arrive at a 95 per cent probability threshold for the climate analogue of VaR, it is necessary to evaluate damage with $\text{CS} = 9.3^{\circ}\text{C}$. This

is more than twice the conventional ‘upper-bound’ benchmark of 4.5°C .

It is therefore useful to consider costs and benefits of greenhouse abatement using a CS of 9.3°C , rather than the base CS value of 2.9°C value in the DICE99 model in the analyses of the previous two sections. Abatement policy based on this parameter might be thought of as at least an approximation of identifying society’s ‘value-at-risk’ up to a probability of 95 per cent. Alternative terminology for the same thing would be a ‘minimax’ strategy, which minimizes the maximum risk (up to a ‘maximum’ of 95 per cent probability).

Figure 1.13 returns to the DICE99NB baseline for emissions and radiative forcing to examine the influence of increasing the CS parameter. Figure 1.13 shows radiative forcing (wmsq^{-2}) and warming ($^{\circ}\text{C}$) for the base and high-warming cases ($\text{CS} = 2.9^{\circ}\text{C}$ and 9.3°C). An important feature of the high-warming case shown in figure 1.13 is that equilibrium warming at the CS occurs with a much longer lag from the date of realized $2 \times \text{CO}_2$ radiative forcing when the CS is higher. Thus, the radiative forcing corresponding to a doubling of carbon dioxide is 4.4 wmsq^{-2} . If a grid is drawn to the horizontal axis, the NB baseline shows this amount of radiative forcing by 2075. For baseline warming, the corresponding warming of 2.9°C occurs in 2125, giving a thermal lag between committed and realized warming of fifty years. In contrast, for the high-warming case, the CS warming of 9.3°C does not occur until 2285, meaning that the thermal lag has lengthened to 210 years.²⁵ This effect tends to soften the potential damage, but also raises the question of whether the 300-year horizon is sufficient for analysing the effects of the 95 per cent probability CS.

²⁵ Wigley and Schlesinger (1985) first analysed the lengthening of the thermal lag for higher climate sensitivity parameters.