The Challenge of Global Warming

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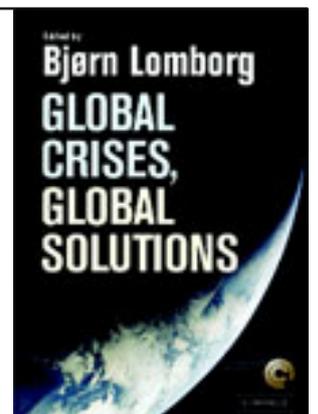
Meeting the Challenge of Global Warming[1]

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Introduction

This paper is part of the Copenhagen Consensus initiative of Denmark's National Environmental Assessment Institute. This initiative seeks to evaluate costs and benefits of alternative public policy actions in a wide range of key policy areas. For comparability, each of the studies in this program identifies a limited number of policy actions and examines their respective costs and benefits. This paper 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 paper must be devoted to the conceptual framework and key assumptions used in modeling costs and benefits from abatement of global warming.

The first section of this study briefly reviews the state of play in the scientific and international policy deliberations on global warming. It summarizes the key findings of the 2001 review of the Intergovernmental Panel on Climate Change (IPCC) and reviews the status of the Kyoto Protocol. The second section discusses crucial methodological components that can drive sharply contrasting results in cost-benefit analyses of global warming abatement, including especially the question of appropriate time discounting for issues with century-scale time horizons. The third section briefly reviews the findings of my own previous studies on this issue as well as those of a leading climate-economic modeler. The fourth section sets forth 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 Annex A. The fifth through seventh sections present this study's cost-benefit analyses 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 perhaps two decades the central stylized fact of global warming science has been that the "climate sensitivity parameter" (referred to hereafter as CS) is in a range of 1.5°C to 4.5°C equilibrium warming for a doubling of

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atmospheric concentration of carbon dioxide from pre-industrial levels.[2] The 2001 international review (Third Assessment Report, TAR) did not change this benchmark (IPCC, 2001a). However, it did increase the amount of expected realized warming by 2100.[3] Whereas the 1995 Second Assessment Report (SAR) had projected that by that date there would be realized warming above 1990 levels of 1.0°C to 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 sulfate aerosols (which reflect sunlight and thus have a cooling influence) in light of increased expectation that developing countries will follow industrial countries in curbing sulfur dioxide pollution (Barret, 2003, p. 364; Hebert, 2000).

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.[4] "[M]ost of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations" (p. 10).[5] Snow cover has "very likely" declined by about 10 percent since the late 1960s. There was "widespread retreat of mountain glaciers" in the 20th century, and global average sea level rose 0.1 to 0.2 meters. Since the 1950s, the thickness of Artic sea ice in late summer- early autumn has likely fallen 40 percent. It is very likely that precipitation increased 0.5 to 1.0 percent per decade over the 20th century in the mid- and high latitudes (> 30°) of the Northern Hemisphere and by 0.2 to 0.3% per decade in tropical areas (10°N to 10°S), but likely that rainfall decreased by about 0.3% per decade over sub-tropical areas of the Northern Hemisphere (10°N to 30°N). The report judged that it was "likely" that during the 21st 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" (p. 15).

The 2001 report based the range of projected warming on six benchmark scenarios (table 1). In 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 (billion 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 Climate Sensitivity parameters in the various climate (general circulation) models, generates the relatively

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[2] "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 30 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.

[3] Realized warming is less than committed warming at any point in time because of ocean thermal lag.

[4] 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 4 decades of small but relatively steady temperature *decline*, followed by a return to a renewed and more rapid warming trend since 1980 (IPCC, 2001a, p. 3).

[5] The report used "likely" for 66-90% chance, and "very likely" for 90-99% chance.

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).[6] 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.[7]

Table 1. IPCC Emissions Scenarios (GtC)

Case	Description Emissions in:	2050	2100
A1B	Rapid growth, population peaking mid-century, convergence, balanced fossil-nonfossil 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), pp. 14-18.

The central message of the 2001 IPPC 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 warming observed in the past century is largely anthropogenic, and the range for projected warming over the 21st 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. 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 U.S. President Clinton signed the treaty in November 1998, he did not submit it to the Senate for confirmation, recognizing that he could not obtain the required two-thirds majority. In March 2001, President Bush rejected the Kyoto Protocol, on grounds that the science was uncertain and that the targets could be costly to the U.S. economy. In addition, there was a strong sense in the U.S. congress that any international treaty would have to include

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[6] 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.

[7] 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 this century, as coal generates almost twice as much in carbon emissions per unit of energy (26 kg per million British thermal units) as natural gas and about one-fourth more than oil (Cline, 1992, p. 142).

developing countries in commitments on emissions ceilings; and the U.S. Senate had voted 95-0 in the summer of 1997 that the United States should not sign any agreement that failed to impose emissions limits on developing as well as industrial countries and that would harm U.S. interests (Barrett, 2003, pp. 369-71).

Despite the U.S. refusal to ratify the Kyoto Protocol, by March 2001 there were 84 countries that had signed the agreement, and by November 2003 there were 84 signatories and 120 countries that had ratified it (UNFCCC, 2004). However, to take effect the protocol required not only that at least 55 countries sign, but also that countries accounting for 55 percent of the 1990 total carbon emissions from Annex I parties (industrial and transition economies) do so. Russia has been the key to implementation, because in the absence of U.S. 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 2003).

Rejection of the protocol by both the United States 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 only impose its carbon tax policy toward this end if other OECD countries also did so, including the United States and Japan (Barrett, 2003, p. 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 United State 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 cost-benefit analyses, 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 analyzing global warming policy is how to discount future costs and benefits to obtain comparable present values for policy judgments. 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 in 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. Thus, the principal scenarios and projections in the 2001 IPCC review were 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 buildup 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 climate sensitivity parameter.

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 percent 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 forth an approach to time discounting that addresses this issue while remaining fully within the tradition of the literature on social cost-benefit analysis.[8] 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" (p. 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) $\text{SRTP} = \rho + \theta g$,

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 to 1.5, meaning that when per capita consumption rises by 10 percent (for example), the marginal utility of an additional unity of consumption falls by 10 to 15 percent. It is evident from equation 1)

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[8] See Arrow (1966), Feldstein (1970), Arrow and Kurz (1970), and Bradford (1975).

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 percent annually, then even with zero pure time preference, the annual discount rate applied to future consumption would be 1.5 percent (using $\theta = 1.5$).

The tradition of social cost-benefit analysis 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, pp. 270-4) suggests a typical shadow price of capital of 1.6, so 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 percent, based on observed capital market rates.[9] 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 percent, their overall discount rate is thus equivalent to about 4 percent annually (3 percent pure time preference plus 1 percent 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, trivializes the problem of global warming by introducing a severe bias against counting the damage experienced by future generations.[10]

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 suboptimal. A variant on this

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

[10] 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.

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, p. 265). Suppose that society could devote 1 percent 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 mobilized, this approach would not be credible. The extra capital assets thereby obtained would have lifespans of 10-15 years, whereas the lifespan 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 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 U.S. Environmental Protection Agency and other sources, Cline (1992) compiled benchmark estimates for damages that could be expected from warming associated with a doubling of CO_2. These damages turned out to be an aggregate of about 1 percent of GDP (p. 131). The largest damages were in agriculture (about one-fourth 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); forest loss and increased tropospheric ozone pollution (each about one-twentieth of the total). The estimate included a speculative and likely 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 percent 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 percent 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 United States (Fankhauser, 1995, at 1.3 percent of GDP, and Tol, 1995, at 1.5 percent of GDP) and in addition extended the estimates to other parts of the world. A higher estimate of 2.5 percent of GDP damage was obtained by Titus (1992), who however applied a higher $2xCO_2$ warming assumption (4°C) than in the other studies (2.5°). The Fankhauser and Tol studies obtained modestly higher damage estimates for non-OECD countries (1.6 percent and 2.7 percent of GDP, respectively).[11]

Cline (1992) also suggested benchmark damage for very-long-term warming with a central value of 6 percent 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 $2xCO_2$ damage for the United States, 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 U.S. 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 U.S. agriculture, but Cline (1996) suggested that this result was vulnerable to an overly optimistic implicit assumption about 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 basic economic attractiveness of greenhouse abatement as evaluated in a cost-benefit analysis. 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 benefit-cost ratio for action.

Nordhaus and Boyer (2000) make an important contribution in attempting instead to incorporate catastrophic risk directly into the cost-benefit analysis. On a 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 probabilities of catastrophic outcomes. After some upward adjustment for "growing concerns" (p. 88) in scientific circles about such effects, they arrive at estimates such as the following. The expected

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[11] For a survey of damage estimates, see Pearce et al, 1996.

loss in the event of a catastrophe ranges from 22 percent of GDP in the United States to 44 percent for OECD Europe and India (p. 90). The probability of a catastrophic outcome is placed at 1.2 percent for 2.5°C warming and at 6.8 percent 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 percent of GDP in the United States at 2.5°C and 2.53 percent of GDP at 6°C, while the corresponding magnitudes are 1.9 percent and 10.8 percent 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 percent of GDP is initially negative (i.e. beneficial effects) up to 1.25°C warming, but then rises to 1.1 percent of GDP for 2.5°C warming, 1.6 percent of GDP for 2.9°C, 5.1 percent of GDP for 4.5°C, and 10 percent of GDP for 6°C warming.[12] 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 $2xCO_2$ damage at 1 percent of GDP or so.

Adaptation

This study 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 incorporated already 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.[13]

Carbon Taxes versus Quotas with Trading

The analysis of this study examines optimal carbon taxes in 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

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[12] In the DICE99XL version of their model, the damage function (percent of GDP) is: $d = 100x (-.0045T + .0035T^2)$, where T is the amount of warming (°C) above 1990.
[13] Thus, Nordhaus and Boyer (2000, p. 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."

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 receive 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 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 economic benefits of abatement, there are relatively few cost-benefit studies, whereas there are numerous estimates of costs of specified abatement programs. This section will highlight two principal previous studies: Cline (1992) and Nordhaus and Boyer (2000).[14]

Cline 1992 – My study in 1992 examined a 3-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 carbon dioxide 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; and 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 one-half percent annual growth, but even at the slower rate reached an average of about 50 GtC annually in the second half of the 23rd century (Cline, 1992, pp. 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 to 14,000 GtC cumulative emissions (Cline, p. 45, based on Edmonds and Reilly, 1985, p.160), so rising resource costs could not be counted upon to provide a natural choking-

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[14] The Working Group III review for the IPCC in 1995 identified only two other cost-benefit analyses then available, and only one of them (Peck and Teisberg, 1992) was published. Pearce et al, 1996, p. 215.

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 damages amounted to about 1 percent of GDP for the central value by about 2050 (the estimated time of realized warming from CO_2 doubling above pre-industrial levels already by 2025), rising to a central estimate of 6 percent of GDP by 2300 and, in the high-CS case, 16 percent of GDP by 2275 (p. 280).

On the side of abatement costs, several "top-down" modeling studies then available provided estimates, which tended to cluster in the range of about 1 to 2 percent of GDP as the cost of cutting carbon emissions from baseline by 50 percent in the period 2025-50, and about 2-1/2 to 3-1/2 percent of GDP as the cost of reducing emissions from baseline by about 70 percent by 2075-2100 (Cline, 1992, p. 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 percent 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 and higher fuel efficiency standards for vehicles. In addition, numerous studies suggested low-cost carbon sequestration opportunities from afforestation, which could however only provide 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 percent of world product in the first two decades; but that by about 2050 it would cost about 2 percent of world product to cut emissions 50 percent from baseline. By late in the 21st century emissions could be reduced by up to 80 percent from baseline still for about 2 percent of GDP in abatement costs, because of the widening of technological alternatives (Cline 1992, p. 231-32).

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 cost-benefit analysis. Cline (1992) applies the SRTP method with zero pure time preference and conversion of capital effects to consumption equivalents, as summarized above. The study analyzed a global policy of reducing emissions to 4GtC and freezing them at that level. In the base case, the present value of benefits of damage avoided were only three-fourths as large as the present value of abatement costs. However, an examination of a total of 36 alternative cases showed that in several combinations of high damage (CS = 4.5°C, and/or damage exponent = 2 rather than 1.3, and/or base damage = 2 percent of GDP rather than 1 percent in light of unquantified effects) the benefit/cost ratio could reach well above unity. To arrive at an overall evaluation, and to give some weight to risk aversion, the analysis placed one-half 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 benefit-cost ratio of 1.26 for reducing global emissions to 4GtC annually and holding them to this ceiling permanently in the future (p. 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; Nordhaus, 1994; Nordhaus and Boyer, 2000). His results have systematically found that while optimal abatement is not zero, neither is it very large. Thus, the most recent analysis (Nordhaus and Boyer, 2000) finds that the optimal reduction in global carbon emissions is only 5 percent at present, rising to only 11 percent from baseline by 2100. Correspondingly, the optimal carbon tax is only $9 per ton by 2005, rising to $67 by 2100 (pp. 133-35). Optimal policy reduces warming by 2100 by a razor-thin 0.09°C, or from the baseline 2.53°C to 2.44°C (p. 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" (p. 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 paper 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 labor (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 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 percent of gross world product (GWP) to cut emissions from baseline by 10 percent;

only 0.32 percent of GWP to cut emissions by 30 percent; and only 0.97 percent to cut them by 50 percent. Costs then begin to escalate, however, and it would cost 2.3 percent of GWP to cut emissions by 75 percent at that date.[15]

The model is optimized by a search method applying iterative alternative values of the "control rate" (percent cut of emissions from 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.[16] The nearly de-minimus cost of reducing emissions by 10 percent, combined with the Nordhaus-Boyer conclusion that optimal cuts are below 10 percent 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.[17] Their version will be designated as DICE99NB. The preferred version in this study applies several modifications to obtain what will be called the DICE99CL model. Annex A sets for details on these modifications. This section sets forth the reasons for the most important changes.

Rate of Pure Time Preference – For the reasons set forth 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 NB (Nordhaus-Boyer) version, this rate begins at 3 percent, and slowly falls over time (to 2.57 percent by 2055, 2.26 percent by 2105, and 1.54 percent by 2155). Figures 1 and 2 show the optimal abatement profiles (carbon tax and percent cut from 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 percent cuts in emissions from baseline are in the range of 50 percent through most of the 20th century when pure time preference is zero, instead of 5 to 10 percent as in the original case with 3 percent pure time preference.[18]

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[15] 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.

[16] Full optimization of the model allows the savings rate to vary, as well as the carbon abatement rate.

[17] A more thorough analysis could be carried out by adapting the regional Nordhaus-Boyer model, RICE , along the lines done here for the globally-aggregate DICE99 model. This more extensive task was beyond the scope of the present study.

[18] The downward slope in the optimal cut curve in the case of zero time preference is likely exaggerated by the anomaly of a rising linear component of the abatement cost function, as discussed below. The Excel
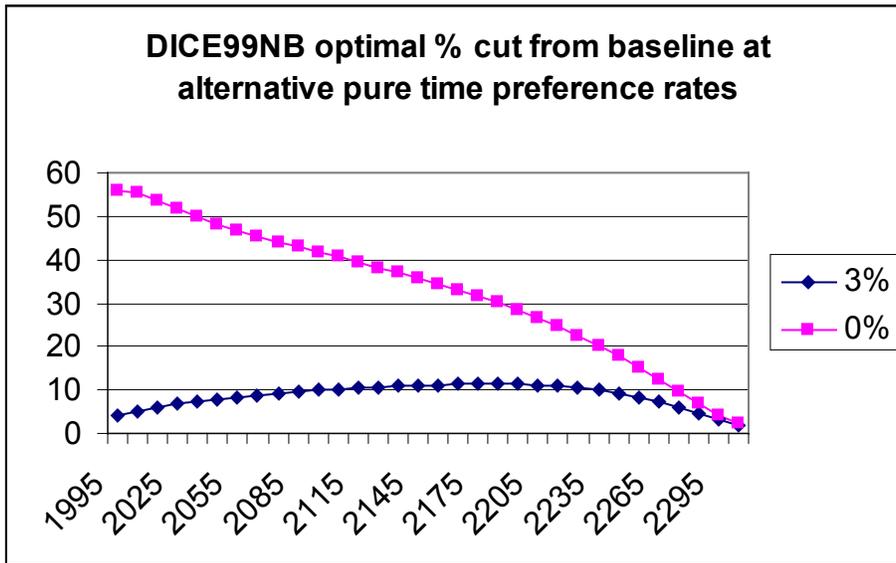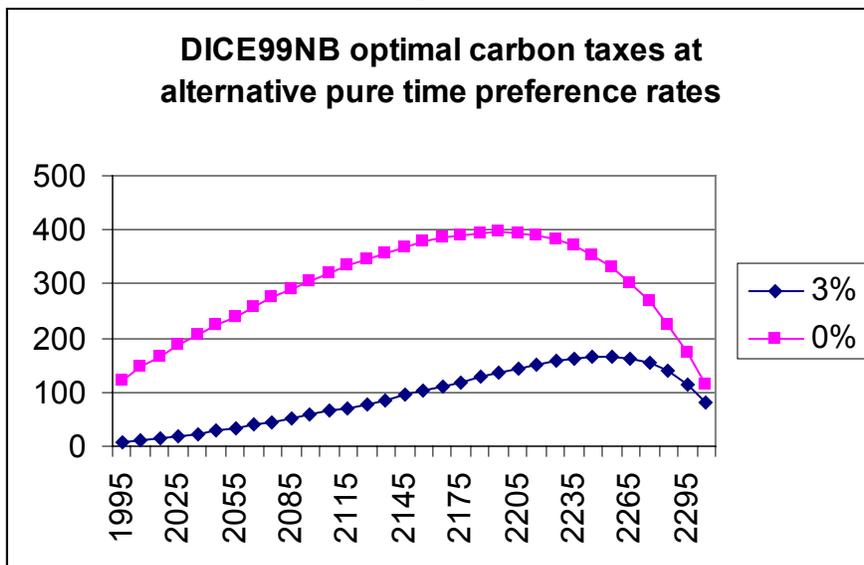
Figure 1

DICE99NB optimal % cut from baseline at alternative pure time preference rates

Figure 2

DICE99NB optimal carbon taxes at alternative pure time preference rates

Figures 1 and 2 refer to optimization of the DICE model with respect to the carbon tax 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 percent over the 21st century rather than 23 percent as in the baseline).[19] However, as discussed above, "full

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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.

[19] For example, in 2195 the optimal carbon tax is 44 percent instead of 41 percent with full optimization, and the carbon tax is $353 per ton insted of $320, for the zero pure time preference variant).

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 Annex A).

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 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 percent lower than before, with population 8.5 percent higher (at 10.7 billion) but output per person 20 percent lower (at $9,100 in 1990 prices), carbon emissions are 48 percent lower than before (at only 12.9 GtC, down from 24.9 GtC; p. 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.
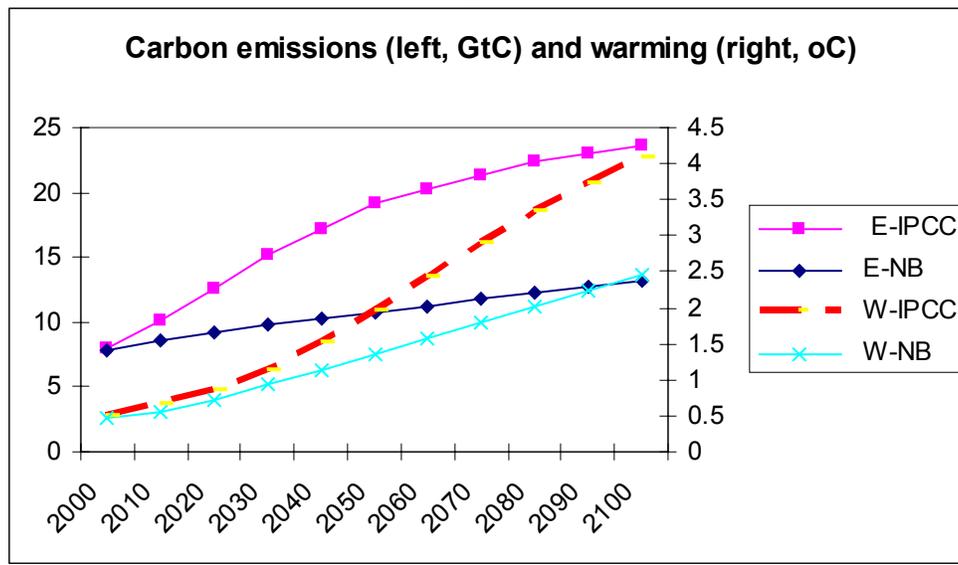
The basis for the sharp reduction in projected carbon intensity of output is not clear, however. In particular, with annual emissions averaging about 10 GtC in the present century, the new Nordhaus-Boyer baseline would only exhaust about one-sixth of the 6,000 GtC cumulative amount available before the 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 above).[20] 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 3 shows the contrast between the 3A's emissions baseline from the IPPC 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 only reach 13 GtC. Figure 3 also shows the average projected

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[20] 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.

baseline warming above 1990 for the 3A's 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 Annex A.

Figure 3

Carbon emissions (left, GtC) and warming (right, oC)

Other Adaptations – As discussed in Annex A, 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 buildup in atmospheric stock. The projections in IPCC (2001) provide a basis for relating atmospheric retention to emissions over this period, and this relationship is used as the basis for the adaptation of the model. This involves relatively modest alterations in the rates of transfer of CO_2 between the various "boxes" of the three-box model, as discussed in the Annex.

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 percent cut from baseline, the economic cost (as a percent 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.[21]

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 adopted model, DICE99CL, is a substantially higher baseline for warming. In the Nordhaus-Boyer (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 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 Nordhaus-Boyer 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, p. 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). The 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 21st 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 17.5wm^{-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.

Policy Strategy #1: Optimal Carbon Tax

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[21] 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 percent in 2020 was 2.1 percent of GWP; by 70 percent in 2050, 2.9 percent; and by 88 percent in 2095, 4.7 percent (Hourcade et al, 1996, p. 336); Edmunds and Barns (1992), Manne (1992), and Rutherford (1992). The corresponding cost estimates using the DICE99 Excel function are 0.7, 2.1, and 4.3 percent, respectively.

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 favorable macroeconomic effects in many countries.

Figure 4 shows the path of the optimal carbon tax and optimal percent 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 percent early on, by nearly 50 percent by 2100, and by a peak of 63 percent 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 Nordhaus and Boyer, 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 and 2).
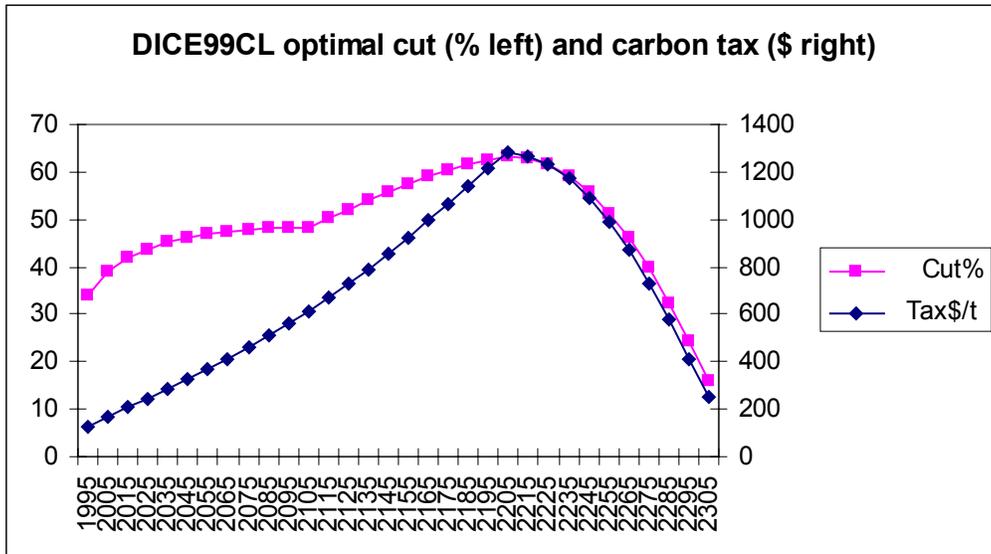
Figure 4

Table 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 percent cuts from baseline).

Table 2

Baseline and Optimal Carbon Emissions (GtC)

	1995	2005	2015	2025	2055	2095	2145	2195	2245	2295
Baseline										
Cline (92)	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 (92)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 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.
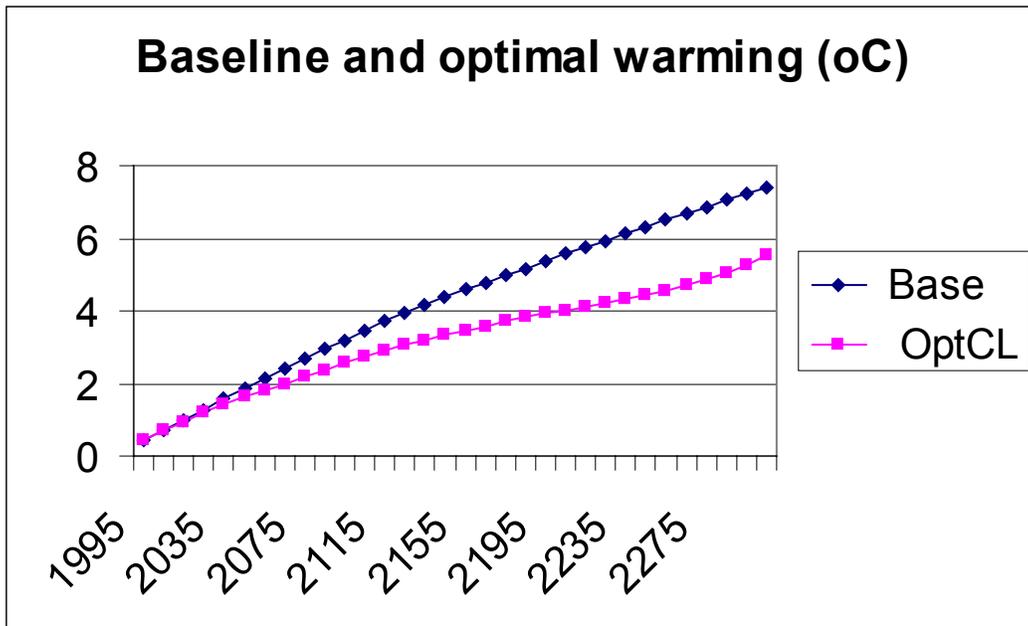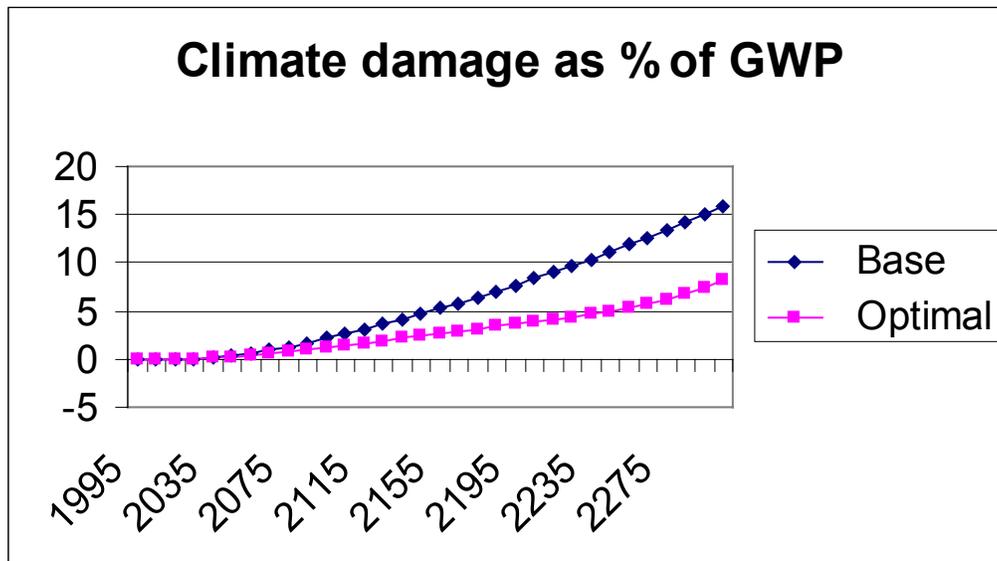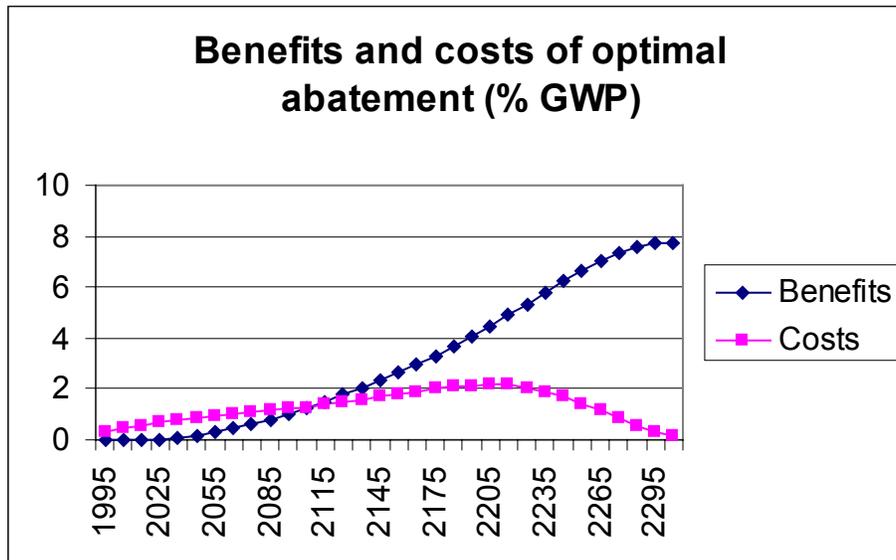
Figure 5

Figure 6 shows climate damage as a percent of GWP in the base and optimal cases. The difference between the two curves represent the economic benefits of abatement. When these benefits are plotted in figure 7 against the abatement costs, both as a percent of GWP, the characteristic timing asymmetry is strongly evident: abatement costs come earlier in the horizon, and benefits of damage avoided only begin to exceed abatement costs after several decades have passed. Even taking account of rising gross world product, it is easy to see from figure 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.

Figure 6

To recapitulate, the first policy strategy, economically optimal abatement, involves an aggressive program that cuts global carbon emissions by an average of about 45 percent from baseline during this century and 55 percent 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 forth above, and applying the percent of GWP abatement costs and benefits of figure 7 to the projection of baseline gross world product, this policy strategy would have a abatement costs with a discounted present value of $128 trillion (1990 prices) and benefits from avoided damage amounting to $271 trillion. The benefit-cost ratio would thus be 2.1.

Figure 7

Benefits and costs of optimal abatement (% GWP)

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 percent of GWP by 2085 and reaching a plateau of about 5 percent of GWP by 2205. (The cost estimate in Cline, 1992, is instead a plateau of about 2-1/2 percent of GWP by 2150 and after; p. 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 1-1/2 percent of GWP for the 23rd century) than in the optimal path (averaging about 4-1/2 percent of GWP through the 23rd century but reaching 8 percent by its end; figure 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 benefit-cost ratio of 1.04. This is far lower than in the optimal case (figure 7, with a benefit-cost ratio of 2.1), but nonetheless shows net positive benefits. The more severe damage function in Nordhaus and Boyer (2000) than in Cline (1992) is the reason why DICE99CL finds a (just barely) favorable benefit/cost ratio for the aggressive stabilization program even though baseline warming in the very-long-term is lower at 7.3°C rather than the 10°C identified in Cline (1992).[22]

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[22] In the central case, the Cline (1992) damage function is less than quadratic with respect to warming, while the Nordhaus-Boyer function is more than quadratic.

Policy Strategy #2: the Kyoto Protocol

The essence of the Kyoto Protocol is to have the industrial and transition economies cut emissions back to 5 percent 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 likely 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. 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 percent.
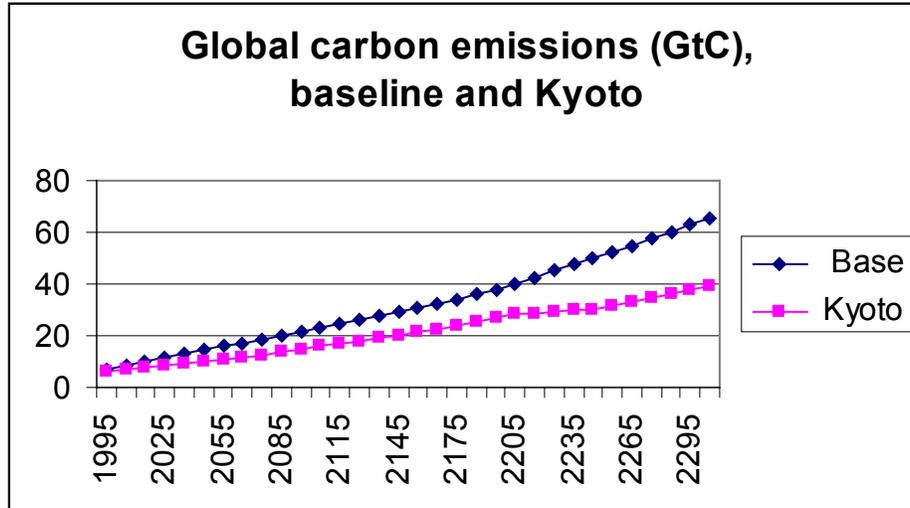
Cline (1992, p. 337) provides a sharply different picture of future industrial country emissions. For industrial OECD plus Eastern Europe and the former Soviet Union, emissions (excluding from deforestation) rise from 4.0 GtC in 1990 to 10.6 GtC in 2100 and 24.4 GtC by 2250. So there is plenty to cut under Kyoto.[23] 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 buildup in emissions from developing countries.

It is possible to use the DICE99CL model as a point of departure for analyzing costs and benefits of the Kyoto Protocol (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 percent 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 8), although far less of a cut than in the optimal strategy of the previous section. The emissions path and

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

all of the rest of the KP analysis assume that all Annex I countries, including the United States, participate.

Figure 8

Global carbon emissions (GtC), baseline and Kyoto

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 percent of world product. Figures 9 and 10 display the baseline and Kyoto paths for warming and climate damage. It is evident in figure 9 that Kyoto is disappointing as a strategy for limiting global warming, as it only reduces warming by 2300 from 7.3°C to 6.1°C. Even so, because of the high degree of nonlinearity in the Nordhaus-Boyer damage function, the result is to cut global climate damage by 2300 from 15.4% of world product to 10.3%.
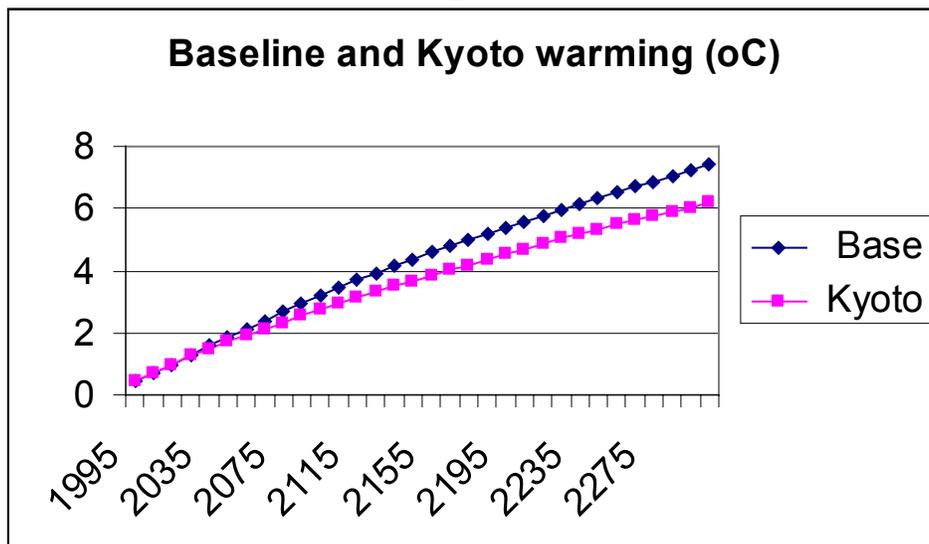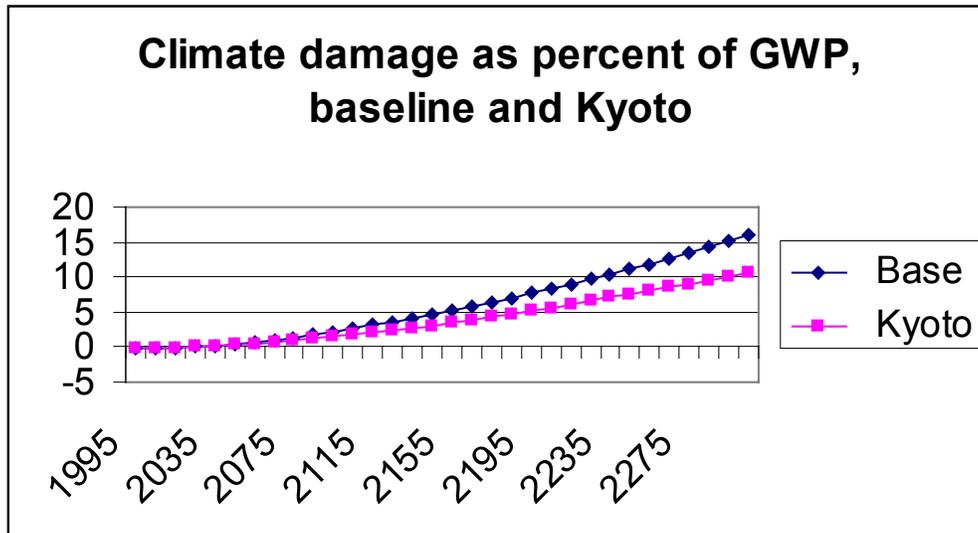
Figure 9

Baseline and Kyoto warming (oC)

Figure 10

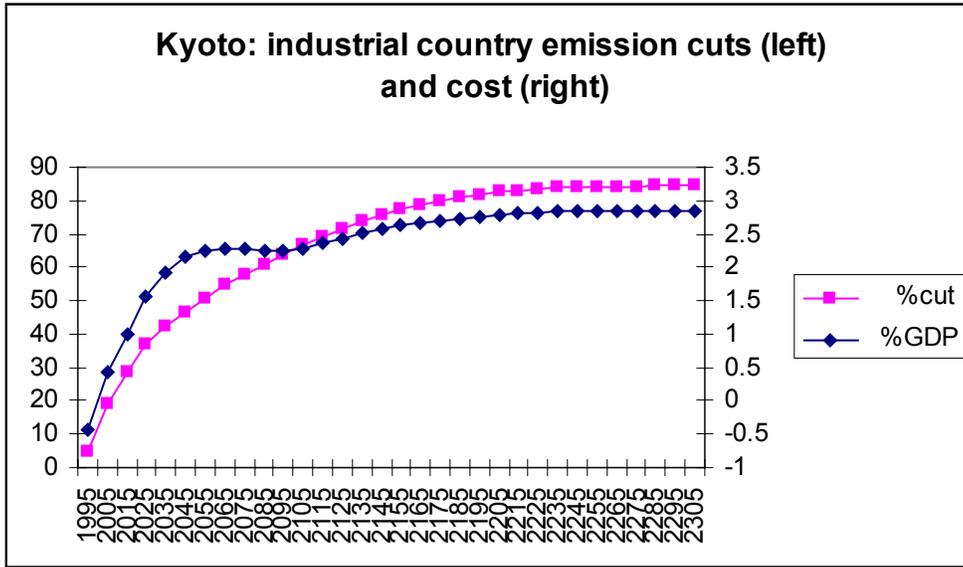Climate damage as percent of GWP, baseline and Kyoto

What remains is to identify the abatement cost of the Kyoto Protocol. 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 subset 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 29 studies with 72 emissions cut scenarios for the United States (p. 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 percent of GDP to the percent cut in emissions from baseline.[24] (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 percent cut from baseline. Abatement cost estimates for Kyoto apply the 2020 regression for 2000-2020 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 percent of industrial country GDP, and percentage cutbacks in emissions from baseline for these countries, are shown in figure 11.
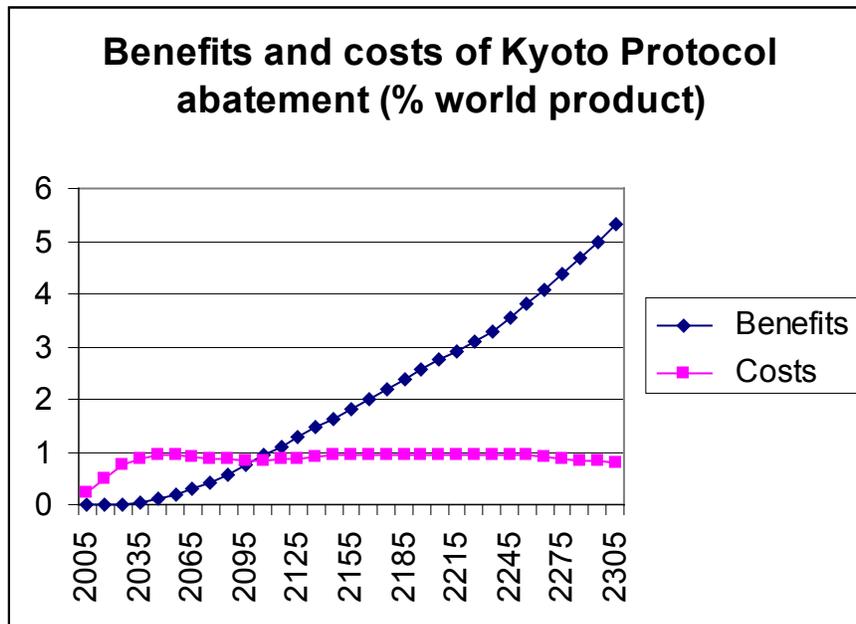
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[24] There are three regressions, one for each of three benchmark dates. For 2020, the result is:
$z = -0.75 \ (-2.1) + 0.061 \ (6.8) \ C$; adj. $R^2 = 0.74$, where z is abatement cost as a percent of GDP and C is percent cut in emissions from baseline (t statistics in parentheses). For 2050:
$z = 0.63 \ (0.7) + 0.0332 \ (2.0) \ C$; adj. $R^2 = 0.16$. For 2100: $z = 0.11 \ (0.33) + 0.0325 \ (6.7) \ C$; adj. $R^2 = 0.73$.

Figure 11

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

Because industrial countries' GDP falls from 56 percent of the world total (ppp basis) in 1995 to 36 percent by 2100 and 28 percent by 2300, the corresponding abatement costs as a percent of world product are progressively smaller over time. Figure 12 shows the Kyoto abatement costs as a percent of gross world product, along with the benefits of Kyoto abatement as a percent of world product. These benefits are simply the difference between baseline-warming climate damage and Kyoto-warming climate damage (from figure 10).

Figure 12

Benefits and costs of Kyoto Protocol abatement (% world product)

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 percent of GDP are the same curve as shown globally in figure 12, for the industrial countries Kyoto benefits only overtake costs 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, then 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 benefit/cost ratio of 1.77.[25] Somewhat contrary to the predominant view, then, the Kyoto Protocol 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 benefit/cost ratio of 0.58.

An important qualification to this estimate is that the benefit-cost calculus might be favorable for Europe as a subregion within the industrial country group. Because the risk of thermohaline circulation shutdown poses the greatest potential damage to Europe, in their regional RICE model Nordhaus and Boyer (2000, p. 160) find that Kyoto emissions ceilings would have a net positive benefit for Europe even in an arrangement in which emissions trading is only allowed within the OECD. This version has significant losses for the United States 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 Kyoto Protocol 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 past decade, 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.

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[25] 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.

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 value at risk 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 Climate Sensitivity parameter, CS (Andronova and Schlesinger, 2001). Using 16 radiative forcing models capturing greenhouse gases, tropospheric ozone, anthropogenic sulfate 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 percent 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 percent probability threshold for the climate analogue of value-at-risk, it is necessary to evaluate damage with CS = 9.3°C. This is more than twice the conventional "upper bound" benchmark of 4.5°C.
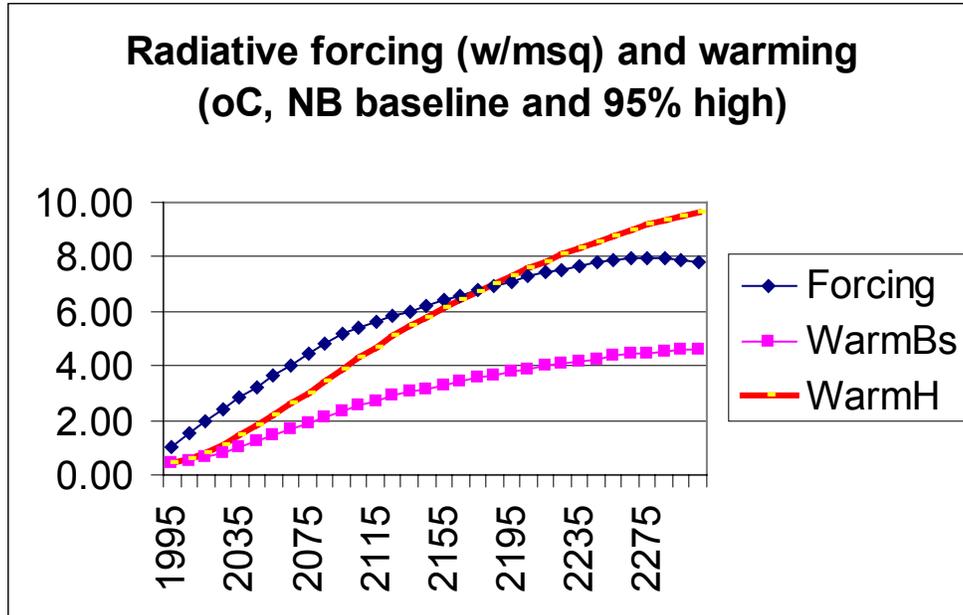
It is therefore useful to consider costs and benefits of greenhouse abatement using a climate sensitivity parameter of 9.3°C, rather than the base CS parameter value of 2.9°C value in the DICE99 model in the analyses of the previous two sections. Abatement policy based on this parameter might be thought of as at least an approximation of identifying society's "value at risk" up to a probability of 95 percent. Alternative terminology for the same thing would be a "minimax" strategy, which minimizes the maximum risk (up to a "maximum" of 95 percent probability).

Figure 13 returns to the DICE99NB baseline for emissions and radiative forcing to examine the influence of increasing the CS parameter. The figure shows radiative forcing (wm^{-2} and °C) for the base and high-warming cases (CS = 2.9°C and 9.3°C). An important feature of the high-warming case shown in the figure is that equilibrium warming at the CS occurs with a much longer lag from the date of realized 2xCO$_2$ radiative forcing when the CS is higher. Thus, the radiative forcing corresponding to a doubling of carbon dioxide is 4.4 wm^{-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 50 years. In contrast, for the high-warming case, the CS warming of 9.3°C does not occur until 2285, meaning the thermal lag has lengthened to 210 years.[26] This effect tends to soften the potential damage, but also raises the question

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[26] Wigley and Schlesinger (1985) first analyzed the lengthening of the thermal lag for higher climate sensitivity parameters.

of whether the 300 year horizon is sufficient for analyzing the effects of the 95% probability CS.

Figure 13

Radiative forcing (w/msq) and warming (oC, NB baseline and 95% high)

In the spirit of a value at risk strategy, it is possible to repeat the optimal abatement analysis of strategy #1 above, once again applying the DICE99CL model but this time implementing it with a CS of 9.3°C. Figure 14 shows baseline warming in that model, along with high-CS warming for the same baseline of emissions and radiative forcing. By 2300, warming reaches 15°C, considerably higher than the 10°C reached in figure 13 because of the higher baseline emissions and radiative forcing in the CL than in the NB version. Optimal abatement policy curbs this warming to 5.9°C by 2300.

Figure 15 shows the corresponding optimal emissions cut from baseline and optimal carbon tax in the DICE99CL model for the case with CS=9.3°C. This time the adapted model's maximum allowed cut of 90 percent from baseline becomes binding.[27] The time path for the optimal carbon tax begins at $450 per ton in 2005 and rises to a peak of $1,900 per ton in 2205.

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[27] Correspondingly, through most of the period the carbon tax needed to arrive at this ceiling cut (at 90% reduction) is considerably below the environmental shadow price associated with climate damage. Thus, as of 2025 (for example), the environmental shadow price is $1,820 per ton of carbon, whereas a carbon tax of $570 is sufficient to cut emissions by the maximum 90 percent.
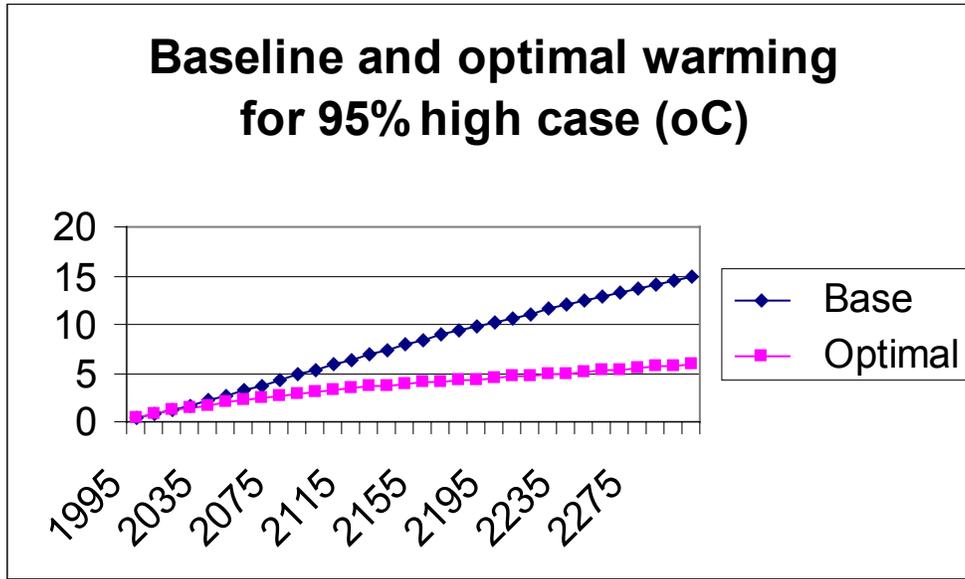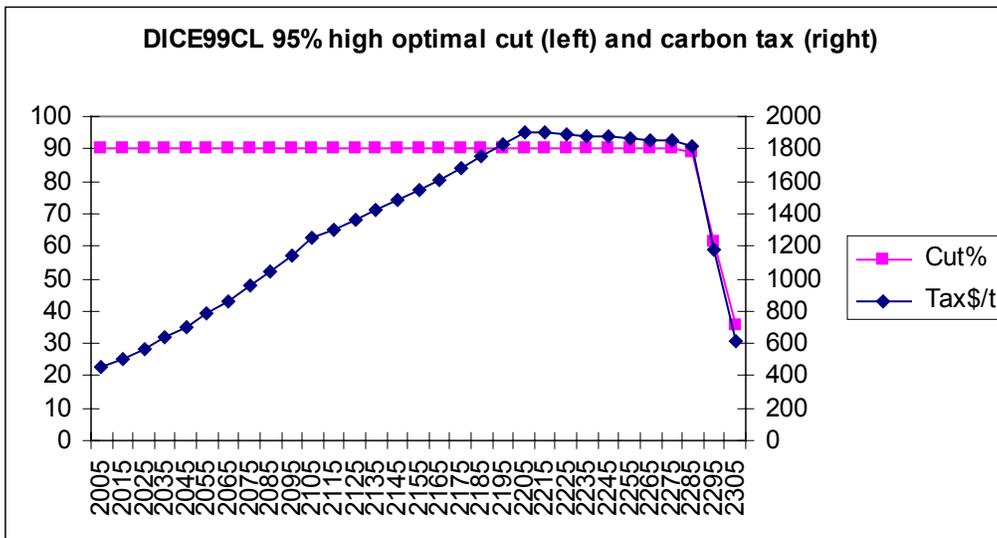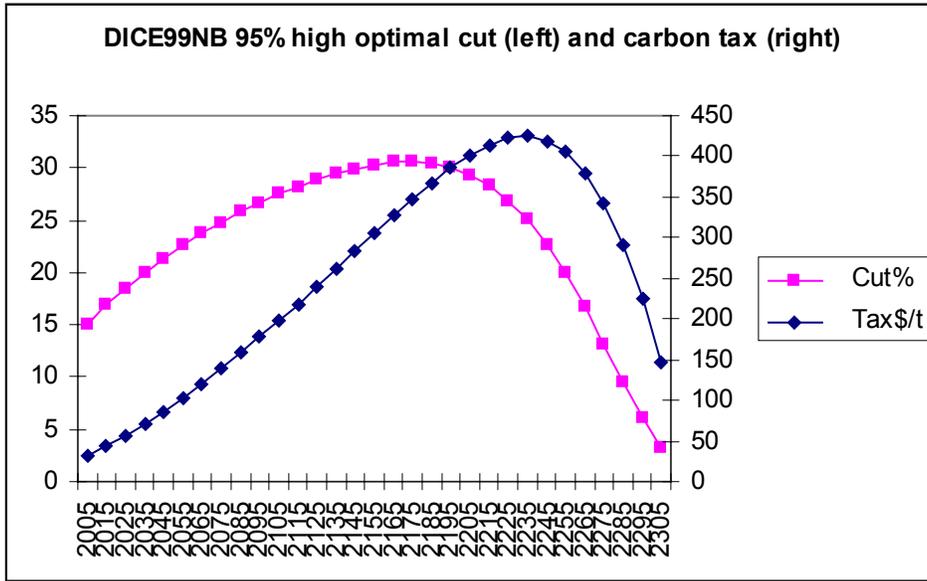
Figure 14

Figure 15

In contrast, it turns out that if the only change to the Nordhaus-Boyer model is to apply the high CS parameter, their optimal cuts and carbon taxes remain moderate. Thus, figure 16 shows that in this test, optimal cutbacks begin at about 15 percent and peak at 30 percent, and the corresponding carbon taxes begin in the range of $32 per ton and peak at $425 per ton. These abatement intensities are far less than in the CL optimal results for high CS, and demonstrate that the effect of higher discounting and a lower emissions baseline in the Nordhaus-Boyer analysis tend to place a relatively moderate ceiling on optimal action even if the 95% high threshold is used for the CS warming parameter.

Figure 16

DICE99NB 95% high optimal cut (left) and carbon tax (right)

Returning to the CL version, when the climate sensitivity parameter is high the warming is sufficiently high (figure 14) to impose massive climate damage on the global economy. Baseline damage reaches 8.6 percent of GWP by 2100 and a remarkable 68 percent of GWP by 2300, given the strongly nonlinear damage function. Optimal cutbacks reduce this damage to 2.1 percent and 9.4 percent of GWP at these two dates, respectively (figure 17).

Figure 17

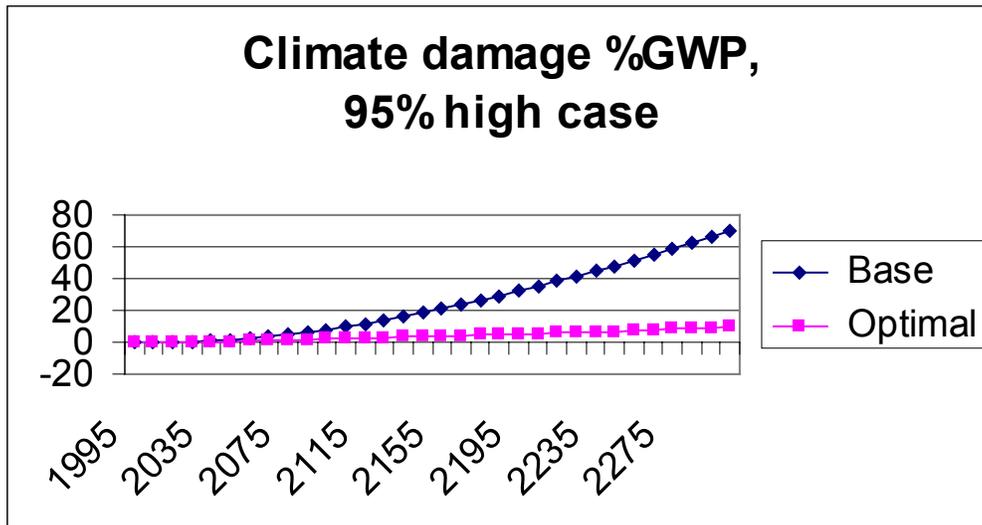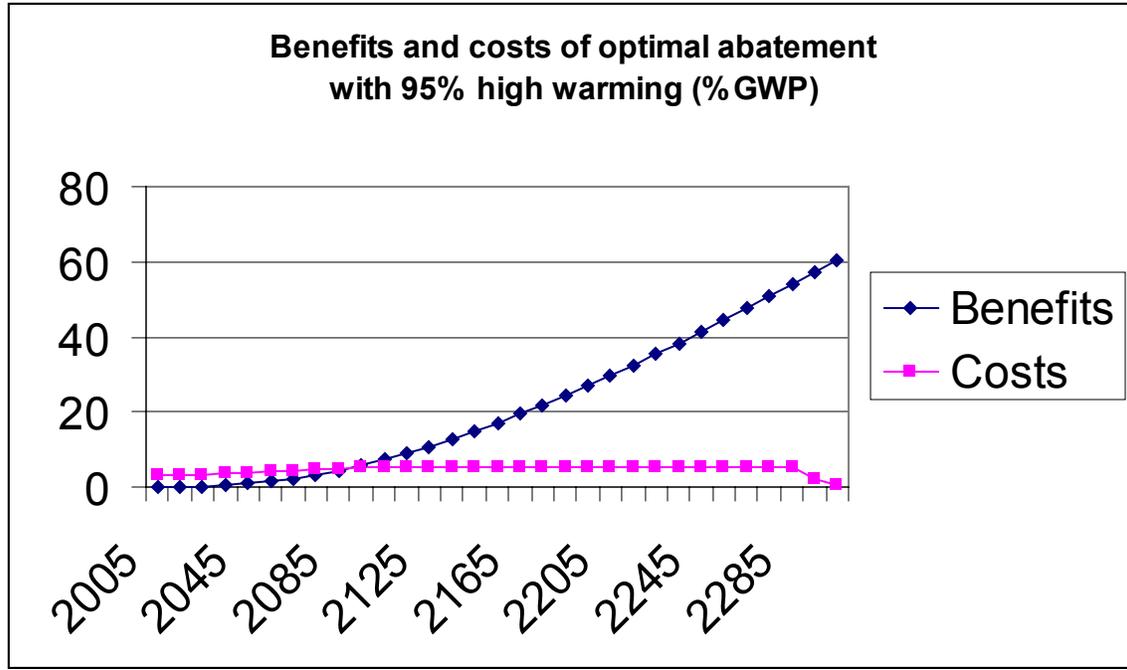Climate damage %GWP, 95% high case

Figure 18 shows the abatement costs of optimal policy under the high-warming case. These average about 3-1/2 percent of GWP in the 21st century and plateau at about 5 percent of GWP thereafter. However, these abatement costs secure a much larger benefit in avoided damages. These benefits, the difference between baseline and optimal

damage in figure 17, are shown in figure 18 to reach about 7 percent of world product by 2100, 17 percent by the middle of the 22nd century, 30 percent by 2200, and ultimately about 60 percent of GWP by 2300.

Figure 18

The discounted present value of benefits of damage avoided amount to $1,749 trillion in the 95% high warming case. The discounted present value of abatement costs is $458 trillion, yielding a benefit-cost ratio of 3.8 to 1.[28]

In summary, in a cautious "value-at-risk" approach in which abatement is based on high warming, with 95 percent probability that the climate sensitivity parameter would be equal to or below the threshold used (CS=9.3°C), optimal cutbacks would be the maximum considered feasible (90% from baseline) over practically the whole of the next three centuries, and carbon taxes would start at about $450 per ton, reach $740 by 2050, $1,200 by 2100, and rise to a peak of about $1,900 in 2200. This seemingly punitive abatement scenario would nonetheless be highly beneficial in net terms, with the present value of benefits of damage avoided almost four times that of abatement costs.
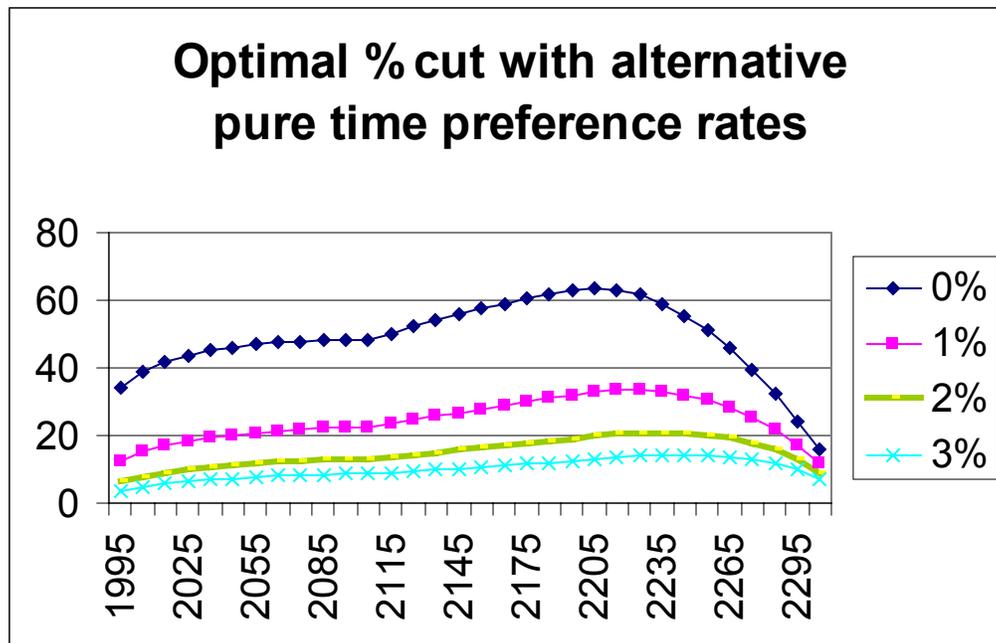
Impact of Alternative Discounting

All of the analyses so far apply a zero rate of pure time preference. Figures 19 and 20 show the impact of applying alternative rates of pure time preference in arriving at

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[28] In the absence of abatement the damage to future consumption would be sufficient to require recalculation of the discount rate, as future period cumulative per capita income growth rates (*g*) would be much lower. The discounted present value of future damages would be considerably higher than using the unadjusted discount rate. However, optimal abatement would constrain damage to a small enough level that the adjustment in the discount rate would be minor.

the optimal abatement path under the central value of the climate sensitivity parameter (2.9ºC for 2xCO$_2$ warming). The strong influence of this change in the discount rate is evident in the figures. For example, if the rate of pure time preference is set at 3 percent, implying a total discount rate of about 4.5 percent annually once the influence of rising per capita income and the elasticity of marginal utility are taken into account, the optimal cutback from baseline emissions remains below 10 percent until the middle of the next century, whereas in this study's central case (zero pure time preference) the optimal cutback is in the range of 40-50 percent in this century and is about 55 percent by the middle of the next century (figure 19). Correspondingly, whereas by 2025 the optimal carbon tax is $245 per ton at zero pure time preference, the optimal tax at this date is $90 at pure time preference of 1 percent, $45 at 2 percent, and only $26 at 3 percent.

Figure 19

The major reduction of abatement found to be optimal in the base case as the pure time preference rate reaches 2 to 3 percent is no surprise. The optimal cutbacks and carbon taxes over the present century are broadly similar to those estimated by Nordhaus and Boyer, who start with a pure time preference rate of 3 percent and allow only a gradual deline in this rate over time. It is perhaps a greater surprise that even in the high damage case the degree of abatement is modest when a pure time preference rate of 2 to 3 percent is used (figures 21 and 22). Thus, whereas the optimal emissions cutback from baseline in the 95% high climate sensitivity case is 90 percent in 2025 with zero pure time preference, the cut drops to 58 percent with 1 percent pure time preference, 27 percent with 2 percent, and 15 percent cutback with 3 percent pure time preference. The corresponding optimal carbon taxes also drop off rapidly, from $565 per ton to $339, $139, and $72 per ton, respectively.
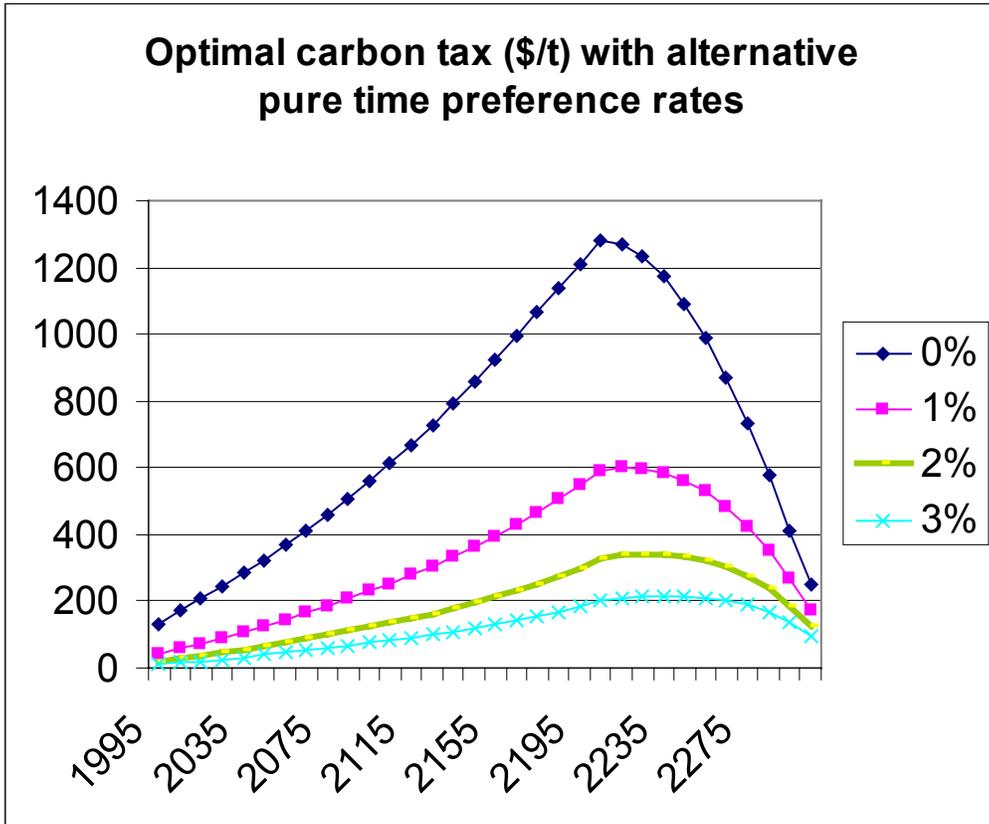
Figure 20

Optimal carbon tax ($/t) with alternative pure time preference rates

Legend: 0%, 1%, 2%, 3%

Figure 21

95% high optimal cut (%) under alternative pure time preference rates
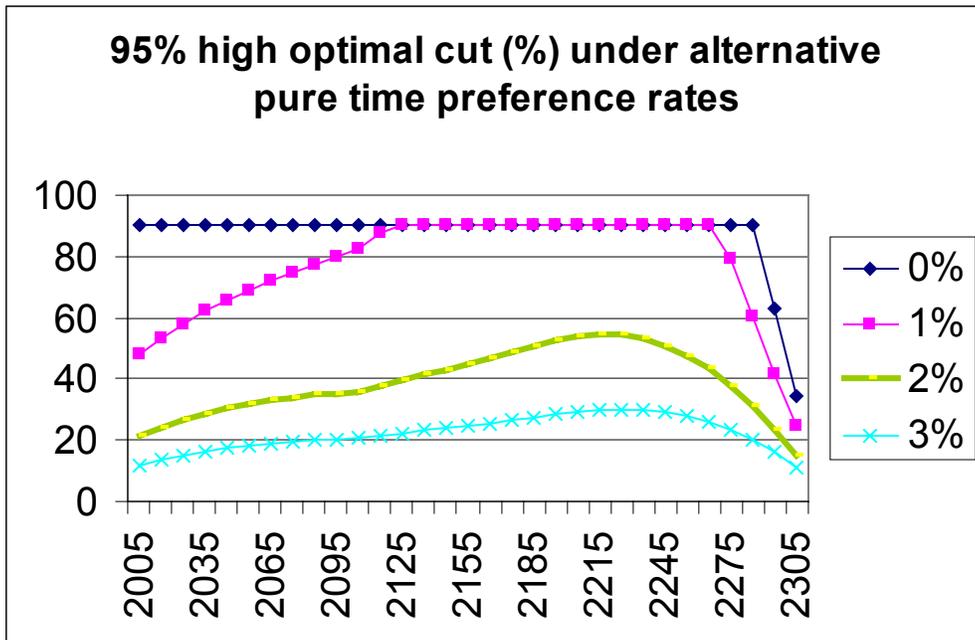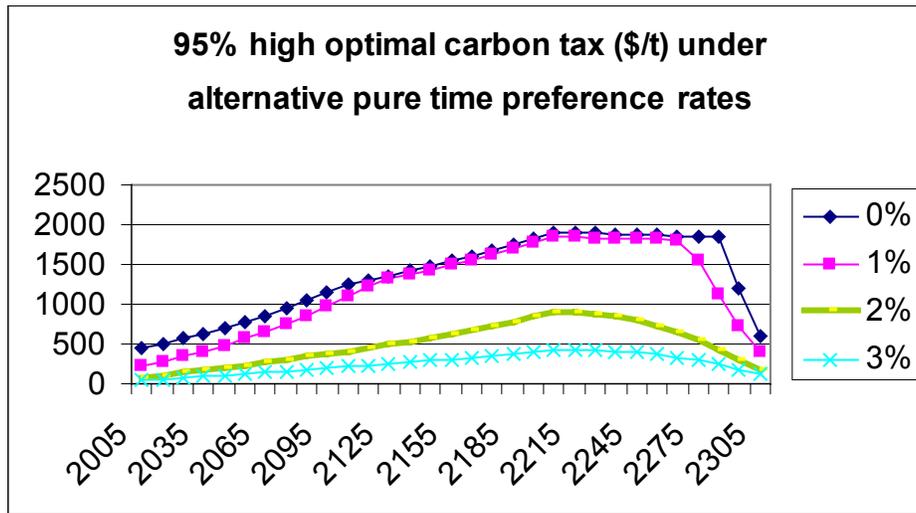
Legend: 0%, 1%, 2%, 3%

Figure 22

The modest abatement at pure time preference of 3 percent even with high climate sensitivity seems to contradict the finding in Cline (1992, p. 302) that an aggressive plan of abatement limiting global emissions permanently to 4 GtC has a favorable benefit cost ratio at 3 percent pure time preference if the climate sensitivity parameter is 4.5ºC, the damage function is quadratic, and damage at 2.5ºC warming is 1 percent of GDP. Considering that the latter two parameters are about the same as in the DICE99 model and the "value at risk" climate sensitivity is a much more severe 9.3ºC here, it is apparently a higher abatement cost function that discourages much abatement in DICE99 even in the face of dramatic warming. Thus, abatement of 90 percent of GWP costs about 5 percent of GDP annually by 2100 in the adapted DICE99CL model, whereas in Cline (1992, p. 280) cutbacks this deep at this time horizon cost only 2.5 percent of GWP. The lower cost in the Cline (1992) calculation reflects the assumption there that a "backstop technology" becomes available for non-carbon energy by that period, as argued by Manne and Richels (1991). [29]

An alternative way to examine the influence of the discount rate is to consider the impact on the discounted present value of benefits and costs of the central-result "optimal" abatement path. Table 3 reports the present values of the base case "optimal" abatement path and the "high damage" optimal abatement path identified in policy options #1 and #3 above, at alternative values of the rate of pure time preference. As shown in the table, in both cases the discounted present value of benefits from limitation of climate damage exceeds the present value of abatement costs when the rate of pure time preference is 0 or 1 percent, but benefits fall short of costs when this rate rises to 2 or 3 percent.

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[29] Another factor may be that the "fix" in the model adaptation here placing a ceiling after 2100 to an otherwise rising cost abatement function present in the Excel version of DICE99 (contrary to a declining function in the GAMS version) may insufficiently avoid overstatement of abatement cost by that period.

Table 3
Discounted Present Values at Alternative Rates of
Pure Time Preference ($ trillions and ratios)

Abatement path:	Pure time preference	Benefits	Costs	Benefits /Costs
#1 Optimal, base climate	0%	270.96	128.47	2.11
sensitivity (figure 4)	1%	36.04	35.83	1.01
	2%	7.76	15.88	0.49
	3%	2.45	9.38	0.26
#3 Optimal under 95% high	0%	1,748.52	458.38	3.81
climate sensitivity	1%	229.60	144.07	1.59
(figure 15)	2%	47.45	69.21	0.69
	3%	14.26	41.76	0.34

Conclusion

This study has applied an adapted version of the DICE99 climate-economic model developed by Nordhaus and Boyer (2000) to examine the costs and benefits of alternative abatement strategies for dealing with global warming. The crucial model adjustments involve adopting zero pure time preference (but allowing for above unity elasticity of marginal utility) in arriving at the proper time discounting for century-scale time horizons; and reverting to a much less optimistic baseline projection of carbon emissions than in the new Nordhaus-Boyer estimates, which are far lower than in Nordhaus (1994). Table 4 summarizes the benefit-cost results for the three strategies examined.

The first strategy is to identify and adopt an optimal path for abatement of carbon emissions, based on a carbon tax. Implicitly this tax is globally uniform, but it would be nationally collected and used. Using the adapted model (DICE99CL), the optimal reduction in carbon emissions from baseline averages about 45 percent in this century and 55 percent in the next. A carbon tax in the vicinity of $150 per ton would be applied over the next decade, rising to $600 by 2100. Global warming would reach 3.4°C by 2100 and 7.3°C by 2300 in the baseline. Warming would be reduced under optimal abatement to 2.6°C by 2100 and 5.4°C by 2300. The discounted present value of benefits of damages thereby avoided would amount to twice the present value of abatement costs.

It should be noted that this strategy involves much more aggressive abatement than that identified in Nordhaus and Boyer (2000), who place the optimal carbon tax at less than $10 per ton in the near future and only about $60 by 2100, and who correspondingly estimate optimal cutbacks from baseline at only about 5 percent in the near term, rising to only about 11 percent by 2100. It is also important to note that the policy of aggressive abatement suggested in Cline (1992), stabilizing global emissions at 4GtC annually, would just barely have present value benefits in excess of present value

of costs. Although it would be less optimal than the path identified under policy #1, it would limit warming substantially more (to 2.1°C by 2100 and 3.1°C by 2300). It could thus be more appealing than the optimal strategy identified as policy #1 to those who consider that even the substantially non-linear damage function in the Nordhaus-Boyer model (adopted also in the DICE99CL version here) may understate potential damage.

Table 4

Benefit-Cost Summary, Discounted Present Values[a]
(trillions of dollars at 1990 prices, and ratios)

	Optimal carbon tax (A)	Kyoto Protocol (B)	Value-at-Risk carbon tax (C)
Benefits	271	166	1,749
Costs	128	94	458
Benefits/Costs	2.12	1.77	3.82
Annualized benefits	0.90	0.55	5.83
Annualized costs	0.43	0.31	1.53

a. All cases use social rate of time preference for discounting. This equals the rate of pure time preference, set to zero, plus the amount of discounting to take account of improving living standards. The latter equals the elasticity of marginal utility (set at 1.5) multiplied by annual growth rate for per capita income (approximately 1 percent). All cases examine a 300 year horizon.

A. Base case optimization yields a carbon tax beginning at $128 per ton of carbon equivalent, rising to $600 by 2100 and $1,300 by 2200. Global warming limited to 5.4ºC by 2300 instead of baseline 7.3ºC. Carbon cutbacks are 30-50 percent from baseline in 21st century, 50-60% in 22nd century.

B. Industrial and transition economies adhere to Kyoto Protocol emissions targets; developing countries unrestrained from baseline emissions growth. By 2200 global emissions are 30 GtC instead of 40 GtC in baseline. Global warming limited to 6.1ºC by 2300 instead of baseline 7.3ºC. Costs of abatement fully borne by industrial countries. Benefits of abatement are only 0.58 of costs, for these countries.

C. 95%-high climate sensitivity parameter of 9.3ºC warming for $2xCO_2$ used to calibrate costs and benefits. Baseline warming reaches 15ºC by 2300. Optimal emissions cutbacks are identified as maximum allowed in model (90 percent), limiting warming by 2300 to 5.9ºC. Optimal carbon tax begins at $450 per ton, reaches $1,900 per ton by 2200.

        The second policy strategy specifically examined is the Kyoto Protocol. The model results indicate that this policy has a benefit/cost ratio above unity, but has several limitations. Because only the industrial and transition economies curb emissions, and given the large increase expected in emissions of developing countries not subject to limits, the Kyoto Protocol attains considerably less limitation of future global warming and damages than under optimal policy. Warming would reach 6.1°C by 2300, rather than 5.4°C in the optimal policy. Moreover, for the industrial and transition economies subject to the Kyoto controls, the discounted present value of benefits would be less than the present value of abatement costs, as much of the benefits would accrue to the developing countries not restraining their emissions. The only question about this strategy is whether it warrants implementation as "better than nothing." In part the

answer depends on whether the climate policy area should be viewed as an additional area in which industrial countries should make income transfers to developing countries. Moreover, answering this question requires thinking about whether such transfers should be made over a centuries-scale horizon.

The third policy strategy is a risk-averse "value at risk" approach. By analogy with common practice in financial firms, global authorities might wish to base climate policy on projections that consider the damages that could occur up to a probability of 95 percent that they would be no larger. For this purpose, it is possible to apply a recent estimate of the probability distribution for the climate sensitivity parameter (CS). Andronova and Schlesinger (2001) estimate that this parameter would have to be as high as 9.3°C for a doubling of carbon dioxide to provide 95 percent confidence that warming would be no higher. When the (adapted) model is applied using this parameter, global warming reaches 15°C by 2300. The optimal amount of abatement is the ceiling considered feasible in the model (a limit of 90 percent cutback in emissions from baseline). Optimal carbon taxes begin in the range of $450 per ton and rise as high as $1,900 by 2205. The benefit/cost ratio for this approach is about 4 to one, reflecting the extraordinary levels of climate damage eventually reached in the baseline (about 50 percent of GWP by the second half of the 23rd century). Although many would judge this strategy to be prohibitively costly and unduly risk averse, it should not be dismissed out of hand. Its abatement costs average about 3-1/2 percent of GWP in the 21st century and plateau at about 5 percent thereafter. Many might consider this a price worth paying to assure with a high degree of probability that warming would not reach the extremely high levels that could otherwise be attained.

Annex A

Changes to the DICE99 Model

The DICE99 climate model of Nordhaus and Boyer (2000) is an elegant integrated climate-economic model that provides a basis for analyzing optimal policy on global warming. A key feature of the model is that it examines a 3-century horizon. As emphasized in Cline (1992), this is the proper time-scale for analyzing the impact of carbon dioxide emissions, because it will take this long before the reduction of atmospheric carbon dioxide through mixing into the deep ocean will begin to reverse atmospheric buildup (Sundquist, 1990).

The model (hereafter referred to as DICE99NB) has been made available to the public on the website of William Nordhaus.[30] Some of the text analysis directly applies this model. Most of the analysis, however, applies a revised version prepared by the present author for this study. These revisions have been adopted either because of an alternative conceptual framework (in particular, for time discounting) or because of an alternative long-term outlook for underlying economic variables (e.g. gross world product and carbon emissions). This annex discusses the changes made in the model.

A. <u>Gross World Product (GWP)</u> – Real GWP is changed to track the projections in Cline (1992, p. 290). Purchasing power parity values are used for developing countries. This boosts initial world product from $22.6 trillion (NB) to $35.7 trillion (CL).[31] It should be noted that by using market exchange rates rather than purchasing power parity values, the NB version tends to understate growth of world product because it gives a low weight to the more rapidly growing area. This scalar adjustment also requires a corresponding adjustment to initial world capital stock (from $47 trillion to $74 trillion). GWP in the model is obtained from a production function involving capital (to the exponent 0.3, reflecting the share of capital), labor (to the exponent 0.7, for the share of labor), and a multiplicative term for total factor productivity (TFP). To obtain the same growth path for GWP as in Cline (1992), the growth of TFP is raised from 3.8 percent per decade in NB to 6.5 percent per decade in CL through 2205, then is cut to 3.2 percent. Finally, as expansion of base-period capital stock only increases base-period GWP from $22.6 trillion to $25.8 trillion, the remainder of the expansion to the ppp base world product of $35.7 trillion is obtained by adding an initial multiplicative scalar (=1.38) to the production function.[32]

B. <u>Emissions coefficient</u> – As discussed in the main text, the Nordhaus-Boyer DICE99 carbon emissions baseline sharply reduces projected emissions from the earlier Nordhaus and Yohe (1983) projections used in part in determining the baseline for Cline (1992).

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[30] http://www.econ.yale.edu/~nordhaus/homepage/homepage.htm.
[31] In 1990 prices. For clarity, NB is used to identify the Nordhaus-Boyer version, and CL to identify the adapted version of this study.
[32] The changes reported in this paragraph are made in rows 15, 37, and 71 of the Excel spreadsheet version of DICE99, hereafter referred to as NBDxl.

To return to an emissions baseline that tracks that in Cline (1992), the growth rate of the coefficient of carbon emissions relative to GWP (σ) is moderated from an initial pace of -15.9 percent per decade in NB to -4.6 percent per decade in CL. This pace is held constant through 2205 and thereafter forced to zero to adhere to the Cline (1992) baseline.[33]

C. <u>Non-carbon radiative forcing</u> – "Exogenous forcing" from non-carbon greenhouse gases (O_t) is set in the NB model to start at -0.2 wm^{-2} (watts per square meter) in 1995, rise to +0.2 wm^{-2} by 2025, and continue rising until it reaches a plateau at 1.15 wm^{-2} by 2095. The initial negative figure appears to reflect the NB treatment of net cooling from sulphate aerosols. In the 2001 international scientific review, however (IPCC 2001a, pp. 7-8), radiative forcing as of 2000 above 1750 is estimated (all in wm^{-2}) at 1.46 for CO_2, 0.48 for methane, 0.34 for halocarbons, and 0.15 for nitrous oxide, for the "well-mixed" greenhouse gases, meaning 0.97 for the non-carbon well-mixed greenhouse gases. Radiative forcing is set at -0.15 for stratospheric ozone depletion, +0.35 for tropospheric ozone, -0.4 for sulfate aerosols, -0.2 for biomas aerosols, -0.1 for organic carbon from fossil fuel burning, and +0.2 for black carbon from fossil fuel burning, with a sum of -0.3 for these non-well-mixed greenhouse gas effects. The report also states that of the well-mixed greenhouse gases, by 2100 only one-third of the radiative forcing will come from the three non-carbon gases.

Radiative forcing from non-carbon greenhouse gas sources in the base period (1995) can thus be set at 0.97 for WMghgs (well-mixed greenhouse gases), and -0.3 for NWMghgs (non-well-mixed), or a net of 0.67. In the CL baseline, which as discussed in the main text is close to the IPCC A series scenarios (excluding AT), by 2105 the atmospheric stock of carbon dioxide stands at 1478 GtC (in comparison to 1220 in NB), providing radiative forcing of 5.35 wm^{-2}. So one-third of this amount for the non-carbon WMghgs would amount to 1.76 wm^{-2}. If we freeze the contribution of NWMghgs at their initial net level of -0.3, then by 2105 "exogenous forcing" would rise to 1.46 wm^{-2}. On this basis, the CL version of DICE99 sets O_t at 0.67 wm^{-2} in 1995, rising linearly to 1.46 wm^{-2} by 2105 and remaining constant thereafter.[34]

D. <u>Pure time preference</u> – Pure time preference in CL is set to zero, as discussed in the main text.[35]

E. <u>Shadow-pricing capital</u> – The social cost-benefit approach set forth in Cline (1992) uses zero pure time preference, but also places additional weight on capital effects to take into account the gap between the social rate of time preference (solely based on utility discounting once pure time preference is zero) and return on capital. This is done by applying a "shadow price of capital" to convert capital effects into consumption

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[33] Row 22 in NBDxl. The "rate of decrease in the growth rate of sigma" (row 23 in NBDxl) and the "Acceleration parameter" (row 24) are correspondingly both set at zero. In addition, the initial coefficient is rescaled from 0.274 to 0.165 GtC per trillion dollars of GWP to account for the larger value of ppp GWP (row 20).

[34] Row 54 in NBxl.

[35] Accordingly, in NBDxl both rows 63 (initial social rate of time preference) and 64 (rate of decline) are set to zero.

equivalents. This effect is incorporated into CL by expanding abatement costs to take into account the extra consumption-equivalent costs associated with that portion of abatement costs likely to be at the expense of capital formation. For this purpose, it is assumed that 22 percent of all abatement costs come at the expense of capital formation (rather than consumption), and that the shadow price of capital is 1.6 (based on Cline, 1992, p. 291).[36] This procedure leans against abatement, because it does not incorporate a similar shadow-pricing of that portion of abatement "benefits" – defined as the reduction in climate damage – that would accrue to increased capital formation as opposed to increased consumption.[37]

F. <u>Discounted utility and welfare</u> – In NB, the discounted present value of utility in a future period equals the shrinking pure social time preference factor, multiplied by period population, multiplied the logarithm of per capita consumption. As discussed in Cline (1992, p. 253), the logarithmic utility function is equivalent to a utility function with the elasticity of marginal utility set at unity. That study suggests that utility-based discounting can more appropriately use a central value of 1.5 for θ. In CL, therefore, the future period-specific utility becomes simply: $U_t = [R_t L_t c_t]/(1 + \theta g_t)^T$ where R_t is the period discount factor based on pure time preference (such that R always equals unity in the principal CL assumption), L is population, c is per capita consumption, θ is the absolute value of the elasticity of marginal utility, g_t is the cumulative average annual growth rate of per capita consumption from the initial year up through the end-year of the period in question, and $T = 10t$ as each period is one decade. Total welfare is then simply the sum of discounted utility over all periods considered.[38]

In the optimal carbon tax solution, the discount factor for each period $[1/(1+\theta g_t)^T]$ is held constant at its baseline level. Otherwise the endogenous change in the cumulative per capita growth rate g alters the discount factor, posing an index number problem. Applying the ex ante discount factor path is analogous to applying a Lespeyres (base period weighted) price index.

G. <u>Atmospheric retention</u> – In the NB baseline for emissions and atmospheric concentration of carbon dioxide, from 1995 to 2095 the rate of atmospheric retention of emissions falls from 70 percent in the first decade to 36 percent in the last decade.[39] In contrast, from the detailed IPCC tables on emissions and atmospheric concentration (IPCC, 2001a, tables II.1 and II.2), it can be calculated that the atmospheric retention rate

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[36] The result is to multiply the abatement cost function, in row 7, by the scalar: $[1+0.22*(v-1)]$, where v is the shadow price of capital.

[37] However, as discussed in Cline (1992, p. 295), perhaps about half of the damages avoided would be in consumption-specific form.

[38] In the Excel spreadsheet, these changes affect rows 94 (U_t) and 95 (welfare), and require insertion of a reference row reporting g_t. Note that the single summary value of welfare is merely 10 times the sum over all periods of U_t.

[39] The rate of atmospheric retention is simply the change in the atmospheric stock of carbon from the beginning to the end of the period, divided by cumulative emissions over the period (which in turn is ten times the average between the annual rates of emissions at the beginning and end of the period).

rises from 49 percent in 2000-10 to 59 percent in 2090-2100.[40] So it is necessary to alter the DICE99 equations determining the transit of carbon dioxide out of the atmosphere ("box 1" in the three-box model) into the biosphere and shallow ocean (box 2).[41] (Box 3 is the deep ocean, which can receive carbon dioxide only from box 2). For this purpose, the CL version changes the coefficients ϕ_{11}, the share of atmospheric carbon from the previous period retained in the atmosphere in the current period, from 0.67 to 0.69; and changes the coefficient ϕ_{21}, for the share of previous-period atmospheric carbon lost to the biosphere-shallow ocean "box," from 0.33 to 0.31. It also changes ϕ_{12}, the share of box 2 carbon absorbed into the atmosphere, from 0.276 to 0.3, and ϕ_{22} (retained in box 2) from 0.609 to 0.585. These changes have the effect of maintaining the average atmospheric retention rate at about 50 percent during the 21st century, which is more consistent with the IPCC projections.[42]

H. <u>Abatement limit</u> – In BN, the cut from baseline emissions can be as high as 100 percent. The cut is driven by a formula that shows percent cut from baseline as a function of the carbon tax. In CL, this formula is altered so as to limit the cut from baseline to no more than 90 percent, on grounds of plausible feasibility.[43]

I. <u>Abatement cost function</u> -- For the reasons set forth in the main text, the linear abatement cost term (b_1, row 7) is constrained in CL to a ceiling reached by 2105, rather than allowed to continue rising.

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[40] Note that the IPCC data are in parts per million (ppm). The stock of atmospheric carbon in GtC is approximately 2.12 times the atmospheric concentration in ppm.

[41] Rows 45-48 in NBxl.

[42] The DICE structure imposes a falling retention rate, whereas the IPCC models do not show this over the period through 2100. The changes adopted in CL yield an average retention rate of 52 percent for this century, beginning at an overstated 97 percent, and falling to 59 percent by 2015-25 and to 44 percent by 2095-2105.

[43] For this purpose, the initial scalar "1000" in row 99 is changed to "888".

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