EPOC HIGH-LEVEL SPECIAL SESSION ON THE COSTS OF INACTION

THE COSTS OF INACTION WITH RESPECT TO CLIMATE CHANGE:

BACKGROUND PAPER PREPARED BY WILLIAM R. CLINE
(CONSULTANT)

14 April 2005

The Costs of Inaction with Respect to Climate Change[1]

William R. Cline
Center for Global Development and
Institute for International Economics

Introduction

1. Meinshausen (2004) notes that “loss of the Greenland ice-sheet might be triggered at [an increase above the pre-industrial level in] local temperatures of approximately 2.7°C … which may correspond to [an increase in] global mean temperatures below 2°C. This loss is likely to cause a sea level rise of 7 meters over the next 1000 years or more ...” Hare and Meinshausen (2004) consider that even under the “lowest emission scenario judged feasible” the mean global warming commitment will reach 1.9°C by 2050 before stabilizing at that level.

2. Sea level rise over a millennium is perhaps the best illustration of the potential divide between what appears to be a majority of highly concerned physical scientists and a significant group of more relaxed economists on the urgency of limiting climate change. Many scientists might judge that 7 meters sea level rise over 1000 years would constitute “dangerous anthropogenic interference” with the atmosphere (a policy criterion in the 1992 United Nations Framework Convention on Climate Change). In contrast, some economists might judge that such distant effects can be safely ignored because of technological change and the impact of discounting.[2]

3. The incorporation of risk is another critical element of analysis. Scientific concern implicitly places considerable emphasis on risk from catastrophic non-linear effects, including the shut-down of thermohaline circulation in the North Atlantic that keeps Northern Europe warm, and various “runaway greenhouse effects” involving strong positive feedback (e.g. release of methane from clathrates and reduced CO_2 absorption of warmer oceans). Alternative sea-level scenarios arriving at “6m in a few hundred years” would also qualify as in the catastrophic group in the view of some (Oppenheimer and Alley, 2004). The benefit-cost studies tend to give lip service to lower-probability, high damage events but tend to exclude them from their calculations.[3] Increasingly, however, the principal choices in climate change policy would seem to center on appropriate policy toward reducing the risk of such events rather than evaluating gradual change under smooth warming trends.

4. This paper first considers the principal trade-offs in the timing of policy response to climate change. It then turns to a synoptic review of the economic literature on costs and benefits of climate change abatement. The discussion closes with an estimate of the potential economic cost that might be associated with delay in abatement, based on the analysis in Cline (2004a).

---

[1] In accepting that the document be made more widely available, some member countries have significant concerns with the content of this paper.

[2] For example, Stokey (2004) suggests a discount rate of 5 percent for evaluating global warming. Discounting at 5 percent annually, USD 1 billion damage 100 years from now is worth only USD 7.6 million today; USD 1 billion damage 300 years from now is worth only USD 440 (four hundred forty dollars) today; and USD 1 billion damage a millennium from now is worth virtually nothing today. Note, moreover, that whereas 2°C might be argued to constitute dangerous anthropogenic interference on grounds of eventual sea level rise, some economists appear to judge that warming up to this level would generate favorable effects rather than damages (Mendelsohn, 2004).

[3] The damage estimates in Nordhaus and Boyer (2000) are an important exception, as discussed below.

5. In the specific calculations of the paper, the costs of inaction are specified in two alternative ways. In the first and likely more relevant formulation, it is assumed that inaction persists for only two decades. The costs of inaction are then calculated as the damage arising from the additional climate change above that identified in the optimal abatement path in Cline (2004a) as a consequence of failing to carry out any abatement in the first two decades, net of the savings in abatement costs thereby avoided. In the second and more extreme formulation, inaction is assumed to be permanent (i.e. there is never any reduction in emissions from their baseline path). In this case the costs of inaction are again the net costs of future climate damage after deducting the savings from absence of abatement, but this time over the full time horizon of three centuries.

Policy Inaction, Abatement Delay, and Efficiency

6. The Kyoto Protocol has now become a reality after being ratified by 141 nations including Russia, whose entry boosted the adhering nations' total emissions over the threshold needed for the treaty to take effect. The 35 industrial country signatories have committed to reducing greenhouse gas emissions to an average of 5 percent below their 1990 levels by 2012. In contrast, the United States (along with Australia) has not ratified the Protocol because of economic costs and because large emitting countries such as China and India are omitted from restraints under the treaty.

7. The United States has emphasized research on technological change in its response to climate change. US government spending related to climate change amounts to USD 4.5 billion per year (Abraham, 2003). This includes USD 1.7 billion over five years for research on hydrogen fuel cell technology, and USD 1 billion over 10-15 years to build the first coal-fired, emissions-free power plant (named FutureGen) based on carbon sequestration.

8. The basic idea of delaying abatement until research could stimulate new technologies, and in order to avoid premature retirement of capital stock, has received some intellectual support from Manne (1992) in particular.[4] An important limitation of this approach, however, is that by omitting any direct price signal (such as a carbon tax) to encourage firms to shift away from carbon-based technology, it presumably sacrifices potential endogenous (i.e. price-responding) technical change.[5]

9. The principal risk of delay, of course, is that atmospheric buildup of carbon dioxide (and other greenhouse gases) might reach a level considered by many to be highly undesirable before the regime shifts from "learning" to "acting". Specifically, the business as usual baseline for carbon emissions applied in Cline (2004a) rises from 8.6 billion tons of carbon (GtC) in 2005 to 11.6 GtC in 2025. Cumulative emissions of 202 GtC would likely cause 101 GtC to reside in the atmosphere (as the atmospheric retention rate is about 50 percent). This would boost carbon concentration from 376 parts per million (ppm) in 2003 (Keeling and Whorf, 2005) to 424 ppm in 2025.[6] Taking account of other greenhouse gases, that would imply total carbon equivalent concentration of 490 ppm.[7] At this concentration, the mean probability of

[4] Manne calls such delay the "learn then act" strategy, and contrasts it with "hedging" by immediate abatement in an "act then learn" strategy.

[5] Note, moreover, that the research effort of about USD 5 billion annually, or 0.04 percent of GDP, is an order of magnitude lower than the amount of resource commitment to abatement found optimal for the initial decade or two in Cline (2004a). In that study, optimal abatement in the first 10-20 years amounts to an emissions cutback from baseline by about 40 percent at an economic cost initially of about one-half of one percent of GDP.

[6] This calculation is based on the relationship of 353 ppm carbon concentration in 1989 to total atmospheric stock of 750 GtC at that time (Cline, 1992, p. 16). By implication, by 2003 the atmospheric stock stood at 799 GtC.

[7] Meinshausen (2004) places total radiative forcing from greenhouse gases at 550 ppm carbon equivalent when carbon itself is 475, implying a ratio of 1.16 for total to carbon forcing.

overshooting 2°C warming commitment would be approximately 62 percent.[8] So if such a threshold is judged highly undesirable, two decades would appear too long to learn before acting.

10. Suppose instead that an aggressive abatement program sought to hold emissions to 4 GtC annually (as suggested in Cline, 1992). Over two decades atmospheric concentration would probably rise only to about 390 ppm.[9] With total carbon equivalent correspondingly at say 450 ppm, the probability of overshooting 2°C warming would drop to 47 percent (Meinshausen, 2004), still uncomfortably high for many but giving slightly better than even odds of remaining within this ceiling.

11. The broad thrust of these considerations is that delaying abatement in favour of research increases the odds of reaching climate thresholds which some might consider as dangerous. It could also impose steep "catch-up" abatement costs in subsequent decades as there could be a need for more severe emissions reductions in order to limit atmospheric concentrations (Cline, 2004b).[10]

Benefits and Costs of Climate Change Abatement: a Brief Survey

12. One approach to climate change policy is to seek to identify some dangerous thresholds of concentrations and climate change and then to pursue the least-cost means of reducing emissions enough to remain below these thresholds. An alternative approach is to use benefit-cost analysis to identify optimal abatement policy. This section reviews leading studies in the latter approach.

13. At the outset, it should be emphasized that the later studies tend to take more explicit account of the role of adaptation than the earlier studies. For example, Nordhaus and Boyer (2000) adopt lower estimates of damages in some areas such as agriculture, sea-level rise, and energy than used in some of the earlier estimates because of greater recognition of damage amelioration through adaptation.

14. *Cline (1992)* – My early study emphasized that the horizon for global warming analysis was 300 years, the period required for carbon dioxide concentrations to begin falling again through mixing into the deep ocean (Sundquist, 1990). On the basis of business as usual emissions projections then available, I estimated that emissions would reach about 20 GtC by 2100 and 50 GtC by 2300.

15. Using the scientific relationships reported in the first IPCC (Intergovernmental Panel on Climate Change) review (IPCC, 1990), I calculated that in the absence of action warming could eventually reach 10°C. Estimates by the US Environmental Protection Agency and other sources provided the basis for calculating that at benchmark $2xCO_2$ warming of 2.5°C, damages for the United States would amount to about 1 percent of GDP (p. 131). These were, in order of importance, in agriculture; electricity requirements for greater increased cooling than reduced electric heating; water supply; sea-level rise; loss of human life; tropospheric ozone pollution; species loss, and forest loss, along with other categories with

[8] The mean probability of overshooting 2°C warming at 550 ppm carbon-equivalent concentration is estimated by Meinshausen (2004) at 85 percent; at 450 ppm, the mean probability is 47 percent. The text estimate is an interpolation. Actual realized warming would occur some two decades later than the date of atmospheric concentration "committed" warming because of ocean thermal lag.

[9] With continued atmospheric retention at 50 percent the concentration would reach 395 ppm, but there would be some reduction in the retention ratio with emissions this much lower given ongoing transit from the atmosphere to the ocean and biosphere.

[10] That is, because abatement costs are nonlinear, total cost could be much larger from a scenario of two decades of no abatement followed by two decades of 50 percent cuts from baseline, for example, than from a scenario of gradually rising cutbacks by, say, 20 percent in the first decade rising to 30 percent in the fourth decade with the same total amount of emissions avoided. This abstracts from considerations of premature retirement of capital stock.

smaller effects. I applied a mild non-linear function to arrive at a corresponding central estimate of 6 percent of GDP damages for 10°C warming.

16. The analysis then identified abatement costs on the basis of a survey of top-down and bottom-up models available at the time. After a phase of low-cost abatement through efficiency increases and afforestation, additional abatement was estimated to cost in the range of USD 100 to a ceiling of USD 250 per ton of carbon. I applied social cost-benefit discounting, which converts all effects to consumption equivalents and then discounts at the social rate of time preference (discussed below). The analysis then calculated the benefit-cost ratio for limiting global emissions to 4 GtC annually and holding eventual long-term warming to about 2.5°C. When some allowance was made for risk of higher-damage variants, the result was that the benefits of such a strategy exceeded the costs. Importantly, this conclusion was reached despite the absence of any calculation of catastrophic effects in the baseline or high-damage variants.

17. *IPCC 1995 Review* – The Second Assessment Report of the IPCC included a review of cost-benefit analyses of global warming abatement (Pearce et al, 1996). It noted that various studies had arrived at similar estimates of US damages for benchmark 2xCO_2 warming: 1 percent of GDP in both Nordhaus (1991) and Cline (1992); 1.3 percent in Fankhauser (1995), and 1.5 percent in Tol (1995), even though there was wide variation in the composition of the damage estimates by category.[11] Studies extending the estimates globally found them higher in non-OECD countries (1.6 percent of GDP in Fankhauser and 2.7 percent in Tol). The IPCC review (p. 215) reported estimates of the "shadow price of carbon," or social cost of damage from an extra ton of emissions, which for the first two decades of this century were in the range of USD 7-USD 27 in estimates by Nordhaus (1994), USD 30-USD 35 in Ayres and Walter (1991), USD 12-USD 18 in Peck and Teisberg (1992), about USD 25 in Fankhauser, and about USD 10 in Maddison (1994). A much wider range of USD 8-USD 186 was reported from Cline (1997) because of the range of discount rates applied there.[12] These prices (all in 1990 dollars) were implicitly the amounts that might be warrant for a carbon tax. The IPCC authors emphasized that the choice of discount rate played a major role in the shadow prices estimated.

18. *Nordhaus and Boyer (2000)* – In an important update of his DICE model (and its regional version, RICE), William Nordhaus and his co-author downscaled Nordhaus' earlier expect path of carbon emissions and warming, on grounds that recent studies suggested higher marginal extraction costs and hence a self-limiting influence on carbon emission.[13] However, they scaled up the estimates of damage at warming magnitudes above 2.5°C to take account of increasing probability of catastrophic effects. They benchmarked these effects on the basis of a survey of expert opinion. For example, they estimated that for the United States, the willingness to pay to avoid catastrophic damages associated with 6°C warming would be 2.5 percent of GDP, while the corresponding willingness to pay would be 11 percent of GDP in Europe and India. Despite the more strongly nonlinear damage function than previously used, given lower baseline emissions the authors still identified approximately the same range of optimal carbon taxes as before, beginning at USD 9 per ton of carbon in 2005 and rising to USD 67 per ton by 2105 (in 1990 dollars; p. 133.) This incentive to abatement, although optimal under the Nordhaus-Boyer assumptions, meant extremely limited reduction in emissions and warming. Cutbacks from baseline emissions would be only 5 percent in 2005, rising gradually to 11 percent by 2105. Warming by 2105 would be cut by a miniscule amount, from 2.53°C in the baseline to 2.44°C under optimal abatement. The driving force

[11] Titus (1992) placed damages at a higher 2.5 percent of GDP but also used higher benchmark warming of 4°C.

[12] My 1993 study published in Cline (1997) was an application of the Nordhaus DICE (Dynamic Integrated Climate and Economy) model using alternative discount rates.

[13] Nordhaus (1994) placed baseline global carbon emissions in 2100 at 25 GtC, but Nordhaus and Boyer (2000) reduced the estimate to 13 GtC.

behind this minimal optimal abatement is the use of a 4 percent discount rate rather than the 1-1/2 percent rate that I consider appropriate for global warming analysis.[14] With the lower discount rate I use, the Nordhaus-Boyer DICE model generates optimal emission cuts from baseline in the range of 50 percent over most of the 21st century, and a carbon tax of USD 240 per ton in 2055 rather than USD 33 (Cline, 2004a).

19. *Jorgensen et al (2004)* – Recent studies that omit any attempt to quantify catastrophic effects tend to find the possibility of either positive or negative effects of global warming in an initial phase of moderate warming. Jorgensen, Goettle, Hurd and Smith (JGHS) investigate the impact of global warming on the United States through 2100 under low, central, and high warming scenarios (warming by 2100 ranging from 1.7°C to 5.3°C, precipitation increase ranging from 2.1 to 6.6 percent, and sea level rise ranging from 17.2 to 98.9 cm). In agriculture, they draw on the optimistic estimates of USNCCA (2001) and the pessimistic studies of Adams et al (1990) to estimate that in the "central" climate scenario (2.4°C global mean warming by 2100, 3.1°C US warming), the average impact on agriculture over the century would be a decline in productivity by 26 percent in the pessimistic school but an increase by 20 percent in the optimistic school. The combination of high warming and low precipitation increase is the most adverse. There are similar competing sets of research showing positive or negative effects for forestry, energy (although for electricity the estimates are strictly negative), and mortality. Their literature base shows negative effects even in the optimistic studies for coastal protection (but with much smaller costs than in the optimistic studies) and water supply (except for a small benefit for low warming).

20. In the optimistic set of estimates, JGHS show climate benefits rising to 1 percent of GDP by 2050 before falling back to 0.75 percent of GDP by 2100 in the high-warming case, with the same turning point occurring in 2075 in the central warming case. The turning point in their optimistic scenarios occurs at about 1.9°C mean global warming. It is in the agricultural and energy sectors that there are initial benefits in the optimistic case, "but only so long as climate change remains below critical levels" (p. v). In the pessimistic set of estimates, there is no initial favorable phase, and damages grow steadily to 0.9 percent of GDP in 2050 and 1.9 percent of GDP in 2100 under high warming, and to 0.75 percent and 1.1 percent of GDP respectively under central warming. If a low precipitation variant is included in the pessimistic scenario along with high warming, damage reaches 1.75 percent of GDP by 2050 and 3 percent of GDP by 2100. Agricultural impacts account for about three-fourths of the estimated effects in both the optimistic and pessimistic scenarios. The authors emphasize that even in the optimistic scenarios, "any benefits from climate change are temporary" (p. 39). They also stress that effects are likely to be larger for other countries where agriculture is a higher share of GDP. Their study also excludes non-market impacts (e.g. shifts in species distribution, reduction in biodiversity, losses of ecosystem goods and services, changes in habitats), which "are far more likely…. to be negative than positive" (p. viii).

21. The overall thrust of the JGHS study is both to remind that some initial effects of global warming might be favorable for the United States and to underscore that they could also be negative and that eventually the effects will turn negative even under the optimistic assumptions.

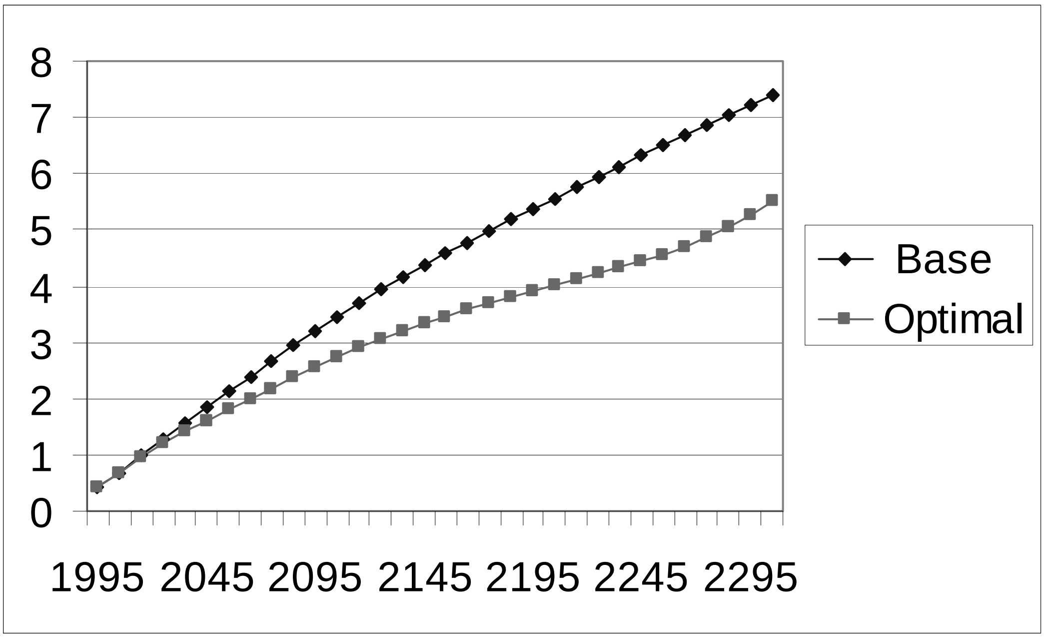
22. *Cline (2004a)* – In my recent study for the Copenhagen Consensus exercise (Lomborg, 2004), I adapted the Nordhaus-Boyer (NB) DICE model to construct a DICE-CL model for examining optimal abatement as well as the Kyoto Protocol. I used their abatement cost function and their climate damage function (which incorporates some weight to catastrophic effects, as described above). The damage

[14] As discussed below, the key difference is in the "pure time preference" or "impatience" component of the discount rate, which Nordhaus and Boyer set at 3 percent and I set at zero. The two studies are much closer in the rate at which they discount for rising per capita income (1 percent, in Nordhaus and Boyer, and 1-1/2 percent in my analysis).

function allows for an initial phase of mildly positive effects.[15] However, I returned the emissions baseline to a higher level more consistent with the more plausible scenarios in IPCC (2001a) and, for example, in Manne and Richels (2001), so that under business as usual, carbon emissions rise from 8.6 GtC in 2005 to 21.4 GtC in 2100 and 38 GtC in 2200.[16]

23. Figure 1 shows the extent of global warming in the baseline and in the "optimal abatement" policy identified in Cline (2004a). Under business as usual, global warming reaches a central estimate of 3.3°C by 2100 and 7.3°C by 2300. When the path of abatement is set so as to maximize the present value of consumption when discounting at the social rate of time preference (discussed below), with lesser warming permitting higher consumption but greater abatement requiring the sacrifice of consumption, the resulting optimal warming path reaches a lower level of 2.6°C in 2100 and 5.4°C by 2300.

Figure 1. Baseline and Optimal Warming (°C)



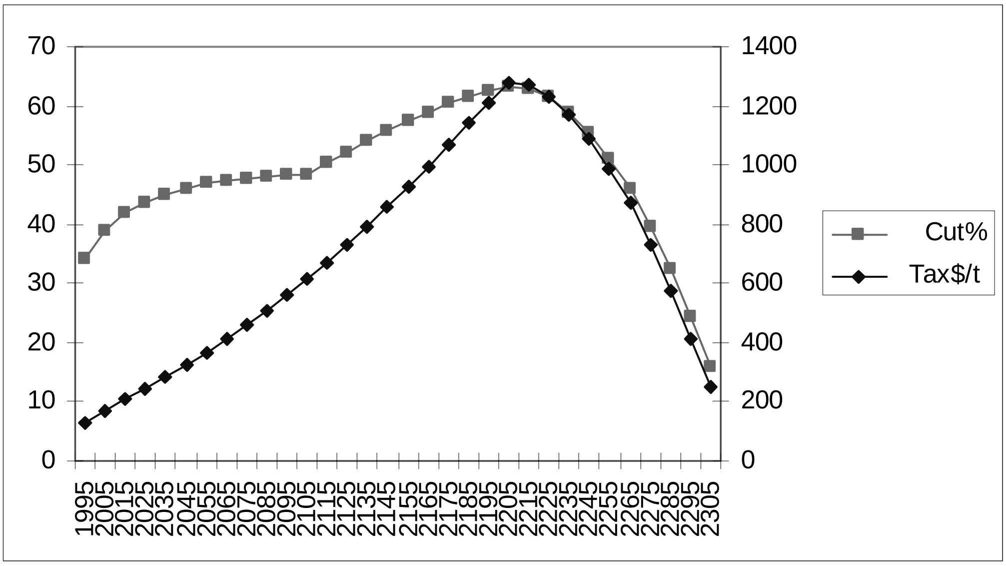
24. The optimal carbon reductions are in the range of 40-50 percent from baseline in the 21st century, rising to a peak of about 65 percent by 2200 (figure 2). The carbon taxes required to carry out these reductions, and equivalently the environmental shadow price of global warming damage, begin at about USD 170 per ton of carbon in 2005, reaching about USD 250 in 2025, USD 600 by 2100, and peaking at USD 1270 per ton by 2200. Note for comparison that USD 100 per ton of carbon would translate into 30 cents for a gallon of gasoline, USD 13 per barrel of oil, and USD 60 per ton of coal. The carbon taxes

[15] The NB damage function is: $d_t = -0.0045\ W_t + 0.0035\ W_t^2$ where d_t is damage as a percent of gross world product and W_t is warming (degrees Celsius) above 1900. The turning point from initial benefits to damage occurs at warming of 0.64°C, where initial benefits reach a maximum of 0.3 percent of GWP. Damages are zero at warming of 1.29°C. At benchmark $2xCO_2$ warming of 2.9°C damage is 1.6% of GWP, and at 6°C damage reaches 9.9% of GWP.

[16] I also modified the parameters for transit of carbon from the atmosphere to the ocean to be more consistent with the atmospheric retention rates in IPCC (2001a). For these and other modifications, see Cline (2004a).

estimated may be overstated, however, because the abatement cost function may overstate carbon reduction costs by about 2050 and beyond.[17]

Figure 2. DICE-CL Optimal Cut (% left) and Carbon Tax (USD right)



25. Figure 3 reports the benefits of avoided climate damage and compares them against abatement costs. The costs occur earlier in the long horizon and the benefits of avoided damage occur later. This illustrates why the discount rate is so crucial in arriving at the optimal policy, because it is necessary to compare costs and benefits across time. Under the optimal policy, it was found that the present value of benefits (damage avoided) over a 300 year horizon amounted to USD 271 trillion, and the costs of abatement, USD 128 trillion, for a benefit / cost ratio of about 2 to 1.

26. The analysis of Cline (2004a) also examined benefits and costs of abatement limiting industrial country emissions to 1990 levels but with no limits on developing country emissions (a permanent version of the Kyoto protocol). Although the overall benefits exceeded costs, there was much less abatement than in the optimal strategy, and for the industrial countries the abatement costs exceeded the benefits. Finally, the analysis considered a "value at risk" approach in which the benefit-cost analysis applied warming thought to be at the 95 percentile high end of the probability distribution (based on Andronova and Schlesinger, 2001). In this case optimal abatement was far more severe, and the damages avoided far larger.

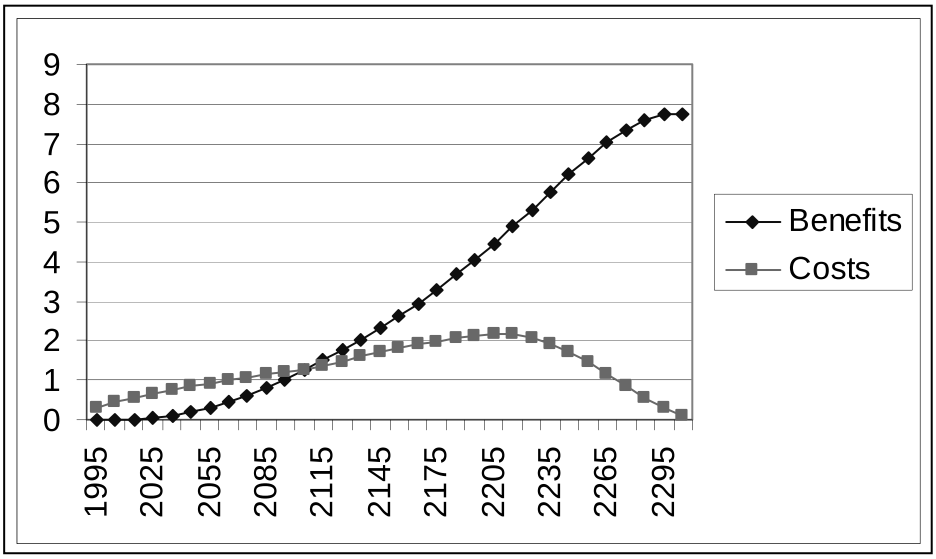
27. In an important additional calculation, Cline (2004a) showed that the aggressive carbon abatement program in my earlier study (Cline, 1992) limiting emissions to 4 GtC annually would have a benefit-cost ratio of slightly above unity (1.04), using the DICE-CL model. This evaluation is important if one places substantial weight on the notion of a "dangerous" level of warming, and considers that the

---

[17] The DICE cost function does not have a non-carbon backstop technology with a ceiling cost (set at USD 250 per ton in Cline, 1992). Moreover, as formulated in the global version of DICE, there is no allowance for declining marginal cost over time from technological change. (See Cline, 2004a for a discussion.) Note further that recent research suggests that carbon sequestration in natural underground formations, combined with a shift of coal-based power to integrated gasification combined cycle (IGCC) technology, could begin to make a non-carbon-emitting backstop technology a reality, at least for the one-third of emissions arising from power generation. See Abraham (2003) and Johnson (2004).

eventual warming of 5.3°C even under optimal abatement exceeds a dangerous level, because as noted earlier, freezing emissions at 4 GtC annually over the indefinite future would appear consistent with limiting warming to about 2.5°C.

Figure 3. Benefits and Costs of Optimal Abatement (% GWP)



28. *Hitz and Smith (2004)* – In a study for the OECD benefits project, Sam Hitz and Joel Smith (HS) have recently surveyed studies of the global impact of climate change. In findings somewhat parallel to those in Jorgensen et al (2004), they find that in some sectors there is a "parabolic" relationship showing some initial benefits from a rise in global mean temperature (GMT) but a reversal toward damages above a certain level of warming, whereas in other sectors there are strictly rising damages. Coastal resources, biodiversity, and perhaps marine ecosystem productivity were found to have increasing adverse impacts with increasing GMT. In contrast, for agriculture, terrestrial ecosystem productivity, and possibly forestry, show initial benefits with a rise in GMT but damages at higher GMT increases. Water, health, energy, and aggregate impacts were found to be uncertain. However, the authors found a consistent pattern that "beyond an approximate 3 to 4°C increase in GMT, all of the studies we examined, with the possible exception of forestry, show increasing adverse impacts" (p. 31). They add the caveat, however, that many impact studies do not look beyond the 21st century, and "for systems in which there is long-term inertia, such as the climate-ocean system, long-term consequences … may be underestimated"(p. 65). In light of concerns about the Greenland ice sheet mentioned at the outset of this paper, it would thus seem especially questionable to infer that warming up to 3-4°C might be benign.

29. For sea-level rise, the authors cite calculations by Fankhauser (1995) placing the cost of coastal protection at a linear USD 10 billion per centimeter increase in sea-level by 2100. For 1 meter increase, this total cost of USD 1 trillion is estimated using a discount rate of zero. In agriculture, HS find that effects below 3°C-4°C increase are uncertain, but emphasize that above 3°C the broad literature suggests crop yield declines; that grain crops experience yield declines above temperature thresholds; that carbon dioxide fertilization effects eventually saturate; and that "eventually … geographical shifting cannot compensate for higher temperatures" (p. 44). They note that Parry et al (1999) find adverse impacts even at 1°C increase in GMT, and Rosenzweig et al (1995) find sharply increasing adverse effects above 4°C (even with adaptation) in contrast to benefits at 2.3°C. They suggest that the projected climate impacts are relatively small compared to baseline increases of agricultural production (output reductions by 20 to 90 million metric tons by 2080 against baseline increases in total output of 4,000 mmt). They stress that the

developing countries could experience more adverse consequences, because of the "longer and warmer growing seasons at high latitudes, where many developed countries are located, and shorter and drier growing seasons in the tropics, where most developing countries lie" (p. 43).

30. Although HS report that the various studies of water stress are inconclusive, they conclude that health risks are more likely to increase than decrease as GMT rises. The studies do tend to show important regional differences, however, with the Mediterranean, Middle East, and parts of Africa and South America identified as likely areas to experience water stress. Model estimates vary in part because of inconsistent estimates of changes in regional precipitation. For health, HS also suggest the patterns are inconclusive. Most studies suggest an increase in health risks with increasing temperature, and in particular a linear increase in potential malarial transmission zones with temperature increase. However, some authors argue that mortality should decrease over time because of improved public health conditions, and that malaria in particular should disappear because of economic growth – an assumption that may be too optimistic. As for mortality from heat and cold, they cite estimates by Tol (2002) to the effect that globally deaths from extreme temperature events should first decline but then turn up again after 2050. However, that study preceded the deadly European heat wave of 2003 (discussed below).

31. On energy use, HS are "highly confident that global energy use will eventually rise as global mean temperature rises" because increased spending on cooling will eventually dominate savings on heating, but they are not certain whether there is an initial phase in which savings dominate. For terrestrial ecosystems, HS survey studies showing an initial growth of the terrestrial carbon sink, followed by reversal at higher temperatures with the decline or death of tropical or temperate forests. Higher carbon dioxide concentrations initially favor plant growth, but this effect saturates (at about 600 to 800 ppm for C_3 plants (such as wheat, rice, and soybeans). Higher temperatures exponentially increase evapotranspiration. On the ability of ecosystems to shift geographical range, one study surveyed indicates that with an increase of 3°C over the 21st century, only 30 percent of ecosystems might be able to adapt. For forests, HS expect a similar pattern of initial gains followed by eventual reversal, and note a lack of studies that correlate results to temperature. Regarding biodiversity, they cite estimates that with a 3°C increase in GMT, "half of all nature reserves will be incapable of upholding their original conservation objectives" (p. 59). In fisheries, HS report the findings of one study predicting a 6 percent global decrease in "export production" (ambiguously defined), comprising a 20 percent decline in low latitudes including the important equatorial Pacific fisheries, mainly from reduced nutrients; partially offset by a 30 percent rise in high latitudes, mainly from increased light efficiency.

32. *Tol, Downing, Kuik and Smith (2004)* – In a study for the OECD benefits project, Richard Tol, Thomas Downing, Onno Kuik, and Joel Smith consider the regional disparities of global warming effects. They conclude that "climate change is likely to impact more severely on the poorer people of the world, because they are more exposed to the weather, because they are closer to the biophysical and experience limits of climate, and because their adaptive capacity is lower" (p. 259). They survey existing regional estimates, and note that the estimates of Nordhaus and Boyer (2000) tend to show greater damage than other studies primarily because they attempt to incorporate some weight to catastrophic effects. They note that Downing et al (1996) stress the high range of uncertainty in damage estimates, from nearly zero impact to nearly 40 percent of world product. At the opposite extreme, they report that Tol (2002) finds remarkably high favorable effects of global warming limited to 1°C in the United States (3.4 percent gain) and Europe (+3.7 percent), but large losses in Africa (-4.1 percent) and South and Southeast Asia (-1.7 percent) even at this small warming. The result in Tol's estimates is that that global effects of initial mild warming are positive if weighted by output (+2.3 percent) but negative if weighted by population

(-2.7 percent).[18] The authors also note that present estimates of climate effects may understate damages because they tend to ignore extreme weather events as well as the compounding effect of multiple stresses.

33. The authors then show how incorporation of equity weighting affects damage estimates. Whereas the "uncorrected" global damages from a doubling of carbon dioxide are estimated at USD 322 billion annually by Fankhauser and USD 364 billion by Tol (i.e. for higher warming than in his 1°C estimates), in the variant giving the greatest weight to equity (utilitarian welfare function with a risk aversion parameter of 1.5) these aggregate damages rise to USD 622 billion and USD 1.06 trillion annually, respectively.

34. *CBO (2005)* – In its most recent assessment of policy toward global warming, the US Congressional Budget Office (CBO, 2005) emphasizes the challenge of identifying a policy strategy given the large scientific and economic uncertainties. It notes recent concerns about possible abrupt changes. It notes that many of the damages would fall in non-market categories, such as damage to ecosystems, posing difficulties in evaluating how much people would be prepared to avoid them. The CBO notes the divergent approaches to discounting, ranging from use of the rate of return on long-term investments, to use of lower rates because of the tax wedge causing investment return to exceed time preferences, to still lower rates based on intergenerational equity. They also note that the more risk averse may prefer more stringent abatement.

35. The CBO researchers consider the implications of disparate regional effects, citing as an example estimates that India might lose 5 percent of output from a 2.5°C rise in global temperature whereas Russia might gain 0.65 percent of GDP. Notably, they argue that "the United States would incur a substantial share of the costs [of global abatement] but would receive a disproportionately small share of the benefits. Developing countries, in contrast, would incur a relatively small share of the costs but would receive a disproportionately large share of the benefits." This provocative judgment would appear to place little value on eventual gains to US citizens' own descendents from limiting global warming, which would surely be subject to challenge if warming well in excess of 2-3°C is considered; moreover, the "share" of abatement costs is better judged by considering costs relative to GDP (which could be substantial for developing countries when and if they join in abatement) in evaluating fair burden sharing.

36. Given the uncertainties, the CBO authors emphasize the importance of choosing a policy instrument that is "most likely to minimize the cost of choosing the 'wrong' level of control," and accordingly judge that "price instruments are much more efficient than quantity instruments" for restricting carbon emissions. They recognize that current research suggests consideration of catastrophic effects can tilt the balance in favor of quantity controls, but note that the conditions for such a shift are not yet met: knowledge of the threshold, projection of rapid escalation of damages beyond the threshold, and knowledge that current emissions are pushing the climate close to the threshold. They recognize the difficulty in identifying the right price in a price-oriented abatement policy, but suggest that the costs of a pricing policy can be moderated by phasing in the prices gradually. They also stress the importance of adaptation as part of the appropriate policy strategy.

Non-linearities

37. It has long been known that catastrophic, non-linear effects might be the most important source of global warming damages. The approach in Cline (1992) was to examine effects without taking these directly into account, and because (with some risk-weighting) the benefit-cost ratio for aggressive action was found favorable, any catastrophic effects were simply considered to be qualitative considerations strengthening the policy conclusion. The approach in Nordhaus and Boyer (2000) is instead to attempt to

[18] The estimates are driven by optimistic assumptions about adaptive capacity and measurement taking into account assumed baseline development trends.

incorporate some monetary valuation of willingness to pay to avoid catastrophic effects into the damage function in the analysis. This section briefly considers what would appear to be important recent developments on such effects.

38. *Asymmetric Warming Probability Distribution* – An important recent trend in the scientific literature is the emphasis on probabilistic treatment of the climate sensitivity parameter – the expected warming for benchmark warming (usually a doubling of atmospheric carbon dioxide equivalent concentration above pre-industrial levels). Andronova and Schlesinger (2001) use 16 radiative forcing models to replicate temperature histories over the past 140 years. After taking account of greenhouse gases, tropospheric ozone, sulfate aerosols, solar forcing, and volcanic effects, they examine the probability density function of the climate sensitivity (CS) parameter implied by the temperature record. The central value long used for climate sensitivity, CS = 2.5°C warming for benchmark CO_2 doubling, was identified in the first IPCC report (IPCC, 1990) and most recently reaffirmed in the Third Assessment Report (IPCC, 2001). The IPCC range of CS=1.5°C to 4.5°C has also remained unchanged. But Andronova and Schlesinger found instead that "there is a 70% chance that it [CS] exceeds the maximum IPCC value of 4.5°C" (p. 4). Indeed, they identified 9.3°C as the value of CS needed to achieve 95 percent probability that warming would be no higher. Several other studies have similarly found a long tail of the probability distribution at high values for the climate sensitivity parameter (see Hare and Meinshausen, p. 12).

39. Cline (2004a) invokes "value at risk" planning in the financial sector to warrant consideration of optimal abatement calculated using CS=9.3°C. Financial institutions identify capital requirements by considering the largest loss they might incur over a period of time, up to a specific level of probability (such as 99 percent). By analogy, there is some merit in considering policy that seeks to limit the maximum damage from climate change up to some limit of probability. Calculating damages under the 9.3°C climate sensitivity parameter, the Andronova-Schlesinger level for 95 percent confidence of no greater warming, yields far higher optimal abatement cutbacks and carbon taxes. Indeed, the cutback is the maximum allowed in the model (90 percent from baseline), and the carbon tax begins at USD 450 per ton and rises to USD 1,900 per ton by 2200. The basic point is simply that most cost-benefit analyses so far have dealt with central values rather than taking a value-at-risk approach focusing on the warming levels that are relevant for achieving a high degree of confidence they will be no worse.

40. *Thermohaline Circulation* – Schneider and Thompson (2000) argue that most economic analyses of global warming, and the widely used DICE model in particular, may underestimate potential damages by assuming "smoothly varying scenarios."[19] They develop a Simple Climate Demonstrator (SCD) that incorporates the impact of shutdown of the "ocean conveyor belt." This phenomenon (thermohaline circulation, TC) involves the sinking of cold water in the Northern Atlantic, its transport southward in the deep ocean, upwelling at low latitudes, and return flow northward in the upper ocean (e.g. Gulf Stream). This mechanism keeps Western Europe some 15°C warmer in winter than it would otherwise be. The paleoclimate record shows numerous instances of reduced or collapsed TC, believed to have been triggered by collapse of ice sheets and release of fresh water. Being less dense than sea water, the fresh water forms a layer on the surface of the Atlantic that impedes sinking. Warming of the water itself also reduces density and sinking potential. There are positive and negative feedbacks, so the rate at which the system is pushed by global warming can determine which of these feedbacks dominate and whether TC collapse would occur.[20]

---

[19] Also see Schneider and Lane (2004).

[20] There is stabilizing negative feedback from the fact that the North-South temperature differential would decline with global warming, and this differential drives the Gulf Stream; with lesser warming influence from the Gulf Stream, local temperatures would not be as high as in the absence of this feedback. Positive, destabilizing feedback from the same deceleration of the Gulf Stream would arise from the fact that there would be a reduced flow of salty subtropical water into the North Atlantic, reducing salinity and sinking potential of the water.

41. In their SCD model, the ocean is described as having two states: one with overturning of water and the other without. Lowering the density of water in the northern Atlantic can trigger a switch from the one state to the other, either by increasing temperature or amount of freshwater. They apply the model using a climate sensitivity parameter of CS=3.0°C. With low stabilization of atmospheric carbon (450 ppm) the strength of overturning falls by about one-third; with the highest concentration considered (1350 ppm), overturning collapses entirely. In the latter case, the north ocean box of the model stabilizes at a temperature 8°C colder than at present, even though the global mean temperature is 3.6°C higher. Similarly, TC collapses if atmospheric concentration is just 750 ppm but the climate sensitivity parameter is 4.5°C. The circulation depends on the rate of CO_2 increase as well as the ultimate level of stabilization. If the pace of atmospheric concentration increase is as high as 1 percent annually, the zone of collapse extends as low as 750 ppm even with the central CS=3.0°C. The authors argue that this rate of stabilization effect "could have a marked impact on the 'timing debate' (e.g. Wigley, Richels, and Edmonds, 1996) in which some argue that delayed abatement is preferable because early abatement is too costly" (p. 74).

42. *Heat Waves* – The Hadley Centre (2004) has recently examined three cases of "high impact climate events." In addition to examining TC collapse and deglaciation of Greenland,[21] the Hadley Centre examined the European heat wave of 2003. That summer was the hottest since modern instrument records began in 1860 and likely the hottest in the last 500 years. An estimated 15,000 excess deaths occurred, along with forest fires and agricultural losses. The Centre examined how much the risk of such an extreme event has been changed by anthropogenic climate change. When such change is omitted, the model estimates indicate extreme warm events are likely to occur only once every 1000 years. With anthropogenic changes included, the model increases this frequency to once very 250 years. The Centre judges that at least half of the risk of the European heat wave of 2003 was due to human activity. It also projects that given baseline emissions, by the 2040s more than half of European summers are likely to be as hot as that of 2003.

Discounting the Future

43. Perhaps the single most important factor in economic analyses of optimal abatement is the discount rate chosen for comparing abatement costs and benefits over time. Figure 3 above shows why this rate is so important: the costs occur early and are ongoing, whereas the benefits of damage avoided tend to occur later and to balloon to truly large values late in the horizon. There are major disagreements among economists about the appropriate way to discount in global warming analysis given the extremely long time horizon involved (see in particular Arrow et al, 1996, and Portney and Weyant, 1999).

44. Cline (1992) suggested that the proper approach to discounting for global warming analysis is to apply the school of social cost-benefit analysis (Arrow, 1966; Feldstein, 1970; Bradford, 1975). This approach is based on the premise that because of tax and other distortions, the observed rate of return on capital is higher than discount rate households use in comparing consumption across time. There is a "shadow price of capital," meaning that one unit of capital is worth more than a unit of consumption. The proper approach for social cost-benefit analysis is then to apply this shadow price to all capital effects, and then to discount all consumption-equivalent effects at the "social rate of time preference" (SRTP). This rate, in turn, is composed of two parts (equation 1). The first part is pure impatience: the rate at which a household might discount future consumption even knowing that it will not be richer in the future. This component is called "pure time preference." The second component is the discount rate applied because the household expects to be richer in the future, and thus expects the marginal utility of extra consumption to be lower than today.

---

[21] In one simulation of the Hadley Centre climate model applying CO_2 stabilization at 1100 ppm, the Greenland ice sheet almost disappears over 3000 years, raising sea level 7 meters. Within the first 1000 years more than half of the ice sheet would be lost, contributing 4 meters to sea level rise.

$$1) SRTP = \rho + \theta g_y$$

45. In equation 1, the first component, pure time preference, is the rate "ρ". The second term on the right hand side captures the effect of falling marginal utility in the future because of a rising standard of living. It equals the rate of growth of per capita income, g_y, multiplied by the "elasticity of marginal utility," or θ (absolute value). This elasticity tells the percentage reduction in marginal utility of an extra dollar of consumption for a one percent rise in per capita income. The most widely used utility function, the logarithmic utility function, has an elasticity of marginal utility of unity. Cline (1992) applies a somewhat higher elasticity of 1.5, giving a somewhat larger discount rate based on rising per capita income than would be the case with a logarithmic utility function.

46. The key dispute on discounting for global warming analysis has been what value to assign to the "impatience" rate of pure time preference, ρ. Cline (1992) follows the father of optimal growth theory, Ramsey (1928), in setting pure time preference at zero. The argument for zero pure time preference is that positive pure time preference penalizes the future generations by judging that, other things being equal (i.e. after applying the second part of the discount rate to take account of rising per capita income), they should accept lower standards of living than those today. Ramsey called it "ethically indefensible" to set pure time preference at a positive level.[22] Even within a single generation and single household, positive pure time preference implies that people are prepared to live impoverished in their old age in order to live in luxury today, which is neither logical nor consistent with how households behave (notwithstanding presently low US personal savings rates, which largely reflect the expectation of rising rather wealth in housing in particular). In contrast, Nordhaus and Boyer (2000) set the rate of pure time preference at 3 percent (although they allow for a slight decline over a centuries-scale horizon). They choose this rate because they believe it is reflects actual behavior, but as noted briefly below, the contrary can be argued about empirical evidence on current behavior. More fundamentally, however, in making decisions that affect the next two or three centuries, underlying principles (such as Ramsey's consideration of what is "ethical") should surely be the basis for policies rather than recently observed market rates. Markets do not extend beyond 30 years, so observable market rates are not available for the relevant period.

47. Because global per capita income growth is set at 1 percent annually over the very-long term, the use of equation 1) above in Cline (1992) effectively applies a discount rate of 1.5 percent (SRTP = 0 + 1.5x1). This is applied to consumption equivalents applying a conversion of capital effects to consumption units at a shadow price of about 1.6 to 1. In contrast, Nordhaus and Boyer effectively have a 4 percent discount rate (3 percent pure time preference plus 1 percent when the logarithmic utility function they use is applied to 1 percent per capita growth). The difference is enormous. For example, USD 1 billion in damages 200 years from today is worth USD 51 million today discounting at 1.5 percent; it is worth only USD 392,000 discounting at 4 percent. Viewed the other way around, discounting at 1.5 percent a person today would feel compensated for giving up 1 dollar if it made his or her descendant better off by USD 20. Discounting at 4 percent, the descendant would have to be better off by USD 2,550 to compensate for giving up just one dollar today. This effect, the shrinking of future effects to today's values for obtaining a single comparison over all future periods, is at the heart of the policy debate on whether global warming is a problem or not. The problem basically disappears altogether if the analyst or policy maker is prepared to discount at such rates a 5 or 10 percent.

48. In the second IPCC review, a team of economists described the difference between the SRTP approach and approaches using observed market rates by the terms "prescriptive" and "descriptive" (Arrow et al, 1996). This dichotomy probably does not do justice to the SRTP approach, because if one searches

[22] Mishan (1975) similarly argued that for intergenerational comparisons this rate should be set at zero because the future generation cannot participate in the decision.

for empirical evidence on the magnitude of the rate of pure time preference, it turns out to be quite low. The best indicator of this rate is the real return on treasury bills, which have no credit risk and no risk from a change in interest rates (being a short-term rate). This real rate has been only about 1 percent over the past several decades. So setting pure time preference at 0 is actually staying closer to the empirical record than setting it at 3 percent.

49. Weitzman (1998) argues that "the far-distant future should be discounted at its lowest possible rate." He arrives at this conclusion by emphasizing the uncertainty about the interest rate itself. When present values of future events are obtained using a certainty-equivalent instantaneous discount rate, the lowest-possible rate turns out to dominate.[23] The essence of the argument is that the "expected" (probability weighted) present value is much closer to the present value obtained using the lowest of the possible discount rates than to that using the highest rate, and that using an average of the two rates will seriously understate the expected present value.[24]

50. Newell and Pizer (2001) adopt this framework of uncertainty about the discount rate itself to analyze implications for discounting in climate change analysis. They present data showing that the real interest rate on US long-term government bonds has fallen from a range of 4-7 percent in the 19th century to a range of 2-4 percent in most of the 20th century, with a brief excursion to 6 percent in the early 1980s. They conduct experiments showing that when the future interest rate is generated by a "random walk" of alternative changes, the benefits from one ton of carbon mitigation rise by as much as a doubling (from about USD 5 to USD 10 if the base rate is 4 percent, or from about USD 20 to USD 30 when the base rate is 2 percent). They emphasize, however, that the incorporation of uncertainty boosts the present value of mitigation by typically less than the adoption of a lower value for the interest rate itself.

Quantifying the Cost of Delay

51. The analysis in Cline (2004a) can be drawn upon to obtain a rough quantification of the cost of delay in the adoption of abatement measures. The adapted DICE-CL model generates the environmental shadow price of carbon for each period. This is essentially the value of damage imposed by an additional ton of carbon equivalent emissions. The model's optimal solution also generates a cost estimate for the abatement undertaken in each period. We can use the shadow price of carbon as the estimate of the benefit from each ton of abatement, and compare it to the cost of abatement. Failure to adopt abatement over a given period of time will then have a cost equal to the difference between the abatement benefits and costs.

52. Table 1 reports the components of this analysis, from the results in the "policy strategy #1: optimal carbon tax" in Cline (2004a).

---

[23] "From today's perspective, the only relevant limiting scenario is the one with the lowest interest rate – all of the other states at that far-distant time, by comparison, are relatively much less important now because their present value has been reduced by the power of compound discounting at a higher rate." (p. 205).

[24] Suppose the probability is 50 percent that the discount rate for the next 100 years will be 4 percent, and 50 percent that it will be 1.5 percent. Discounting at 4 percent, the present value of USD 1 billion in damage 100 years from now is USD 19.8 million. Discounting at 1.5 percent, the present value is USD 225.6 million. The expected value is 0.5x$19.8 million + 0.5x$225.6 million = USD 122.7 million. If instead an average of the two rates is used, or 2.75 percent, the present value is only USD 66.3 million.

Table 1: Annual costs and benefits of optimal carbon abatement, 2005-2025

	2005	2015	2025
Baseline emissions, industrial (GtC)	7.61	9.21	10.75
Optimal emissions, industrial (GtC)	4.64	5.34	6.03
Percent cut from baseline (%)	39.0	42.0	44.9
Shadow price of carbon (USD/tC)	171	208	242
Optimal abatement (GtC)	2.97	3.97	4.72
Benefit value of abatement (USD billions)	508.2	806.1	1154.0
World output (USD trillion, 1990 prices)	48.3	61.1	74.5
Abatement cost as % of world output	0.49	0.61	0.72
Abatement cost (USD billion)	236.5	372.6	536.6
Net abatement benefit (USD billion)	271.7	433.5	617.4
Net abatement benefit, present value	271.7	354.6	424.8

Source: Cline (2004a) and unpublished model results.

53. As indicated in the table, the net benefits from optimal abatement amount to about USD 270 billion annually in 2005, USD 430 billion in 2015, and USD 620 billion in 2025 (all in 1990 prices). Applying the discount rate in Cline (2004a) (which begins at 2 percent and eases to 1.7 percent in the second decade), the corresponding present values amount to about USD 350 billion annually by 2015 and USD 425 billion by 2025. This means that the net benefits of optimal adaptation amount to USD 3.1 trillion in the first decade (present value, i.e. averaging the 2005 and 2015 values and cumulating for 10 years) and USD 3.9 trillion in the second decade. Delaying the adoption of optimal abatement for two decades is thus estimated to cost USD 7 trillion globally in present value terms (at 1990 prices).

54. This calculation assumes that at the end of two decades abatement would suddenly jump to the originally identified optimal path. It would be possible to make other calculations that would allow the implementation of more aggressive "catch up" abatement at the time of the abatement decision, and doing so would tend to reduce the total cost of the delay because there would be lesser emissions after 2025 than in the original optimal path and hence lesser damages. Nonetheless, the simpler calculation here provides a benchmark suggesting that the economic costs of delaying abatement could be large.

Conclusion

55. This paper has focused first on the overall benefits and costs of global warming abatement, and second, on quantifying the costs of delaying policy action. Another approach to the "costs of inaction" would be to consider the costs of complete inaction. If the estimates of Cline (2004a) are used for this purpose, in the optimal policy identified there the discounted present value of abatement benefits is USD 271 trillion, and the present value of abatement costs is USD 128 trillion. So the cost of complete, permanent inaction would be a present value of USD 143 trillion. This net cost already takes into account adaptation, which is incorporated in assessing damages from warming (i.e. the damages would be higher if allowance were not made for adaptation).

56. Numerous uncertainties characterize global warming policy. The climate sensitivity parameter is uncertain. The distribution of precipitation from higher warming is uncertain, and would critically affect whether agriculture in countries such as the United States would tend to benefit or suffer from an initial range of modest warming. Baseline emissions are uncertain, as are baseline growth rates for GDP and population. The probability of a shutdown in the ocean conveyor belt at alternative warming levels is uncertain, as is the time frame in which this might happen.

57. The challenge for policy makers is to adopt appropriate responses in the face of these and other uncertainties about global warming. It is important to recognize that uncertainties do not necessarily mean the best response is delay. Indeed, if the public is risk averse, greater uncertainty can lead to the judgment that there should be lesser rather than greater delay. In the final section above I have attempted to estimate the cost of delay based on my own recent work. The estimate of cost of USD 7 trillion for delay of two decades in abatement implementation suggests that these costs could be high.

58. More broadly, I agree with Schneider and Lane in OECD (2004), who judge that especially because of nonlinearities and surprises, it is a judicious "insurance policy" to "act on policies that slow down the rate at which we disturb the climate system (i.e. abatement policies) … [and] "not become trapped in conventional economic wisdom that suggests we should emit now and abate later" (p. 183). They reach this conclusion in part because of the important role of incentives to technological change provided by mitigation policies, allowing more efficient shifts to non-carbon technology in the future.

59. Finally, the issues reviewed above suggest at least six areas for further research. The first is on improving our knowledge of where the aggregate global damage function from global warming turns negative. Hitz and Smith are careful to say that they do not know the aggregate damage path. However, some might mistakenly interpret their findings that for at least some important effects there are either actual benefits or no damages before about 3-4°C warming as a license for doing nothing for an initial period of time because commitment to that level of warming is not yet near. The study by Jorgensen, Goettle, Hurd, and Smith (2004) is particularly telling about our lack of knowledge as to whether initial warming effects are positive or negative, as they treat the two cases essentially as equally likely (for the United States), identifying a turn to damages in the favorable case only at 2.9°C (as discussed above). Surely this range of uncertainty can be narrowed by further research.

60. Second, greater knowledge of the likely regional distribution of effects, especially identifying impacts on developing countries, would seem to have a high return for further research.

61. Third, it would seem useful to conduct opinion survey work to elicit what "existence value" the public places on avoiding the massive loss of land area that 7 meters sea-level rise would involve, while making it clear to respondents that the time scale is 1000 years. The literature at present seems to point to this effect as the single smoking gun that might warrant calling 2°C warming "dangerous," so it is important to know whether this impact 1000 years from today is considered dangerous enough by the general public that they would be willing to pay something to avoid it.

62. Fourth, it would similarly seem useful to conduct opinion survey work to elicit how the public (and perhaps especially their political leaders) really prefer to evaluate "pure" time preference (discounting for impatience rather than for rising income) on time scales of a century or more. Better knowledge of this rate could substantially affect the overall analysis, because of the crucial role of this concept in comparing costs and benefits across time.

63. Fifth, further research would seem useful in identifying the least-cost path of abatement associated with alternative targets of stabilization of atmospheric concentrations of greenhouse gases.[25]

64. Sixth, additional research is warranted on proper inclusion of adaptation in specification of the damage function for global warming.

[25] Note that Nordhaus and Boyer (2000) provide such estimates for stabilization at twice the level of pre-industrial concentrations. However, as noted above, their baseline emissions and atmospheric retention assumptions would appear understated. Moreover, it would be useful to have an array of optimal abatement paths corresponding to alternative stabilization targets.

References

Abraham, Spencer, 2003. "Announcing the Climate Change Science Program 10-Year Strategic Plan in Washington, DC." (Washington: Department of Energy, July 24). Available at: www.doe.gov.

Adams, R.M., C. Rosenzweig, R. Peart, J. Ritchie, B. McCarl, J. Glyer, B. Curry, J. Jones, K. Boote, and L. Allen, 1990. "Global Climate Change and U.S. Agriculture." *Nature*, May, pp. 219-224.

Andronova, Natalia G., and Michael E. Schlesinger, 2001. "Objective Estimation of the Probability Density Function for Climate Sensitivity," *Journal of Geophysical Research*, vol. 106, no. D19, pp. 22605-12.

Arrow, Kenneth J., 1966. "Discounting and Public Investment Criteria." In A. V. Kneese and S. C. Smith, eds., *Water Research*, pp. 13-32. (Baltimore: Johns Hopkins University Press for Resources for the Future.)

Arrow, K.J., W.R. Cline, K-G. Maler, M. Munasinghe, R Squitieri and J.E. Stiglitz, 1996. "Intertemporal Equity, Discounting, and Economic Efficiency," in James P. Bruce, Hoesung Lee and Erik F. Haites, *Climate Change 1995: Economic and Social Dimensions of Climate Change* (Cambridge, England: Cambridge University Press for the Intergovernmental Panel on Climate Change), pp. 125-144.

Ayres, R., and J. Walter, 1991. "The Greenhouse Effect: Damages, Costs and Abatement." *Environmental and Resource Economics*, vol. 1, pp. 237-270.

Bradford, David F., 1975. "Constraints on Government Investment Opportunities and the Choice of Discount Rate." *American Economic Review*, vol. 65, no. 5, December, pp. 887-899.

CBO, 2005. Congressional Budget Office, "Uncertainty in Analyzing Climate Change: Policy Implications." (Washington: CBO, January).

Cline, William R., 1992. *The Economics of Global Warming* (Washington: Institute for International Economics)

Cline, William R., 1997. "Modelling Economically Efficient Abatement of Greenhouse Gases. In Kaya Yoichi and Keiichi Yokobori, eds., *Environment, Energy, and Economy* (Tokyo: United Nations University Press, pp. 99-122).

Cline, William R., 1999. "Discounting for the Very Long Term." In Portney and Weyant (1999), pp. 131-140.

Cline, William R., 2004a. "Climate Change." In Lomborg, ed., pp. 13-43.

Cline, William R., 2004b. "Rejoinder to Perspective Papers 1.1 and 1.2." In Lomborg, ed., pp. 56-61.

DeCanio, Stephen J., Richard B. Howarth, Alan H. Sanstad, Stephen H. Schneider, and Starley L. Thompson, 2000. *New Directions in the Economics and Integrated Assessment of Global Climate Change*. (Washington: Pew Centre on Global Climate Change).

European Union (2004). Council of the European Union, "Environment." Press Release, 2610th Council Meeting, 14 October. Available at: http://ue.eu.int/ueDocs/cms_Data/docs/pressData/en/envir/82253.pdf.

Fankhauser, Samuel, 1995. *Valuing Climate Change: The Economics of the Greenhouse.* (London: Earthscan)

Feldstein, Martin S., 1970. "Financing in the Evaluation of Public Expenditure." *Discussion Papers* 132. (Cambridge, MA: Harvard Institute of Economic Research, August).

Hadley Centre, 2004. *Uncertainty, Risk and Dangerous Climate Change* (December).

Hare, Bill, 2005. "Relationship between Increases in Global Mean Temperature and Impacts on Ecosystems, Food Production, Water and Socio-economic Systems." Paper prepared for UK Met Office conference on Avoiding Dangerous Climate Change, 1-3 February 2005.

Hare, Bill and Malte Meinshausen, 2004. "How Much Warming Are We Committed to and How Much Can Be Avoided?" PIK Report No. 93 (Potsdam: Potsdam Institute for Climate Impact Research, October).

Hitz, Sam, and Joel Smith, 2004. "Estimating Global Impacts from Climate Change," in OECD (2004), pp. 31-82.

ICCT, 2005. International Climate Change Taskforce, *Meeting the Climate Challenge* (Washington: Centre for American Progress), January.

IPCC, 1990. Intergovernmental Panel on Climate Change, *Scientific Assessment of Climate Change: Report Prepared for IPCC by Working Group I* (New York: World Meteorological Organization and United Nations Environment Programme).

IPCC, 2001. J.T. Houghton et al, *Climate Change 2001: the Scientific Basis* (Cambridge, England: Cambridge University Press for the Intergovernmental Panel on Climate Change).

Johnson, Jeff, 2004. "Putting a Lid on Carbon Dioxide," *Chemical and Engineering News*, December 20, pp. 36-42.

Jorgenson, Dale W., Richard J. Goettle, Brian H. Hurd, and Joel B. Smith et. al., 2004. *U.S. Market Consequences of Global Climate Change*. (Washington: Pew Centre on Global Climate Change).

Keeling, C.D., and T.P. Whorf, 2005. "Atmospheric Carbon Dioxide Record from Mauna Loa." (La Jolla, CA: Scripps Institution of Oceanography). Available at: http://cdiac.esd.ornl.gov/trends/co2/sio-mlo.htm.

Lomborg, Bjorn, 2004. *Global Crises, Global Solutions* (London: Cambridge University Press).

Maddison, D. J., 1994. "The Shadow Price of Greenhouse Gases and Aerosols." Processed, Centre for Social and Economic Research on the Global Environment (CSERGE), University College London and University of East Anglia, Norwich.

Manne, Alan, 1992. *Buying Greenhouse Insurance: the Economic Costs of Carbon Dioxide Emission Limits* (Cambridge, MA: MIT Press).

Manne, Alan S., and Richard G. Richels, 2001. "U.S. Rejection of the Kyoto Protocol: the Impact on Compliance Costs and CO_2 Emissions." Processed. (Stanford, CA: Stanford University)

Mendelsohn, Robert, 2004. "Alternative Perspectives." In Lomborg, 2004, pp. 44-48.

Meinshausen, Malte, 2004. "On the Risk of Overshooting 2°C." (Zurich: Swiss Federal Institute of Technology). Processed.

Mishan, E. J., 1975. *Cost Benefit Analysis: An Informal Introduction.* (London: Allen & Unwin)

Newell, Richard, and William Pizer, 2001. *Discounting the Benefits of Climate Mitigation: How Much Do Uncertain Rates Increase Valuations?* (Pew Centre)

Nordhaus, William D,, 1991. "To Slow or Not to Slow: The Economics of the Greenhouse Effect." *Economic Journal*, vol. 101, no. 407, pp. 920-937.

Nordhaus, William D., 1994. *Managing the Global Commons: the Economics of Climate Change*. (Cambridge, MA: MIT Press).

Nordhaus, William, and Joseph Boyer, 2000. *Warming the World: Economic Models of Global Warming* (Cambridge, Mass.: MIT Press)

OECD, 2004. *The Benefits of Climate Change Policies: Analytical and Framework Issues.* (Paris: Organization for Economic Cooperation and Development).

Peck, S. C., and T. J. Teisberg, 1992. "CETA: A Model for Carbon Emissions Trajectory Assessment." *Energy Journal,* vol. 13, no. 1, pp. 55-77.

Portney, Paul R., and John P. Weyant, eds., 1999. *Discounting and Intergenerational Equity* (Washington: Resources for the Future).

Oppenheimer, Michael, and R.B. Alley, 2004. "Ice Sheets, Global Warming and Article 2 of the UNFCCC." (Princeton, NJ: Department of Geosciences, Princeton University). Processed. October.

Pearce, D.W., W.R. Cline, A.N. Achanta, S. Fankhauser, R.K. Pachauri, R.S.J.Tol, and P. Vellinga, "The Social Costs of Climate Change: Greenhouse Damage and the Benefits of Control," in James P. Bruce, Hoesung Lee, and Erik F. Haites, eds., *Climate Change 1995: Economic and Social Dimensions of Climate Change* (Cambridge, UK: Cambridge Univ. Press for the Intergovernmental Panel on Climate Change), pp. 179-224.

Ramsey, Frank P., 1928. "A Mathematical Theory of Saving." *Economic Journal*, vol. 138, no. 152, pp. 543-559.

SEI 2004. Stockholm Environment Institute, "Scoping Uncertainty in the Social Cost of Carbon," forthcoming.

Schneider, Stephen, and Janica Lane, 2004. "Abrupt, Non-linear Climate Change and Climate Policy," in OECD (2004), pp. 83-110.

Schneider, Stephen, and Starley L. Thompson, 2000. "A Simple Climate Model Used in Economic Studies of Global Change." In Stephen J. Decanio et al, *New Directions in the Economics and Integrated Assessment of Global Climate Change* (Arlington, VA: Pew Centre on Global Climate Change, October, pp. 59-80).

Smith, Vernon L., 2004. "Ranking the Opportunities," in Lomborg, 2004, pp. 630-38.

Stokey, Nancy L., 2004. "Expert Panel Ranking," in Lomborg, 2004, pp. 639-44.

Sundquist, Eric T., 1990. "Long-term Aspects of Future Atmospheric CO_2 and Sea-Level Changes." In Roger R. Revelle et al., *Sea-Level Change*, pp. 193-207. (Washington: National Research Council, National Academy Press).

USNCCA, 2001. United States National Climate Change Assessment, *U.S. Global Change Research Program* (Washington, DC).

Tol, R.S.J., 1995. "The Damage Costs of Climate Change: Towards More Comprehensive Calculations." *Environmental and Resource Economics*, vol. 5, pp. 353-374.

Tol, Richard S.J., Thomas E. Downing, Onno J. Kuik, and Joel B. Smith, 2004. "Distributional Aspects of Climate Change Impacts." *Global Environmental Change*, vol. 14, pp. 259-272.

Weitzman, Martin L., 1998. "Why the Far-Distant Future Should Be Discounted at Its Lowest Possible Rate," *Journal of Environmental Economics and Management* 36 (3): pp. 201-08.

Wigley, Tom, 2004. "Modelling Climate Change under No-Policy and Policy Emission Pathways." In OECD (2004), pp. 221-48.