Rolling the DICE:
Nordhaus' Dubious Case for a Carbon Tax

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[Author's Note: This is a slightly revised version of the article currently under submission. It refers to the DICE model on Nordhaus' homepage after his September 2007 updates. His website now hosts the prepublication version of his 2008 book treatment. The page numbers to Nordhaus herein may therefore be wrong, but the content seems largely the same.]

Abstract

Economists have almost uniformly treated anthropogenic greenhouse gas emissions as a market failure, requiring government measures to counterbalance the negative externality. William Nordhaus, a pioneer and leader in the field, uses the latest calibration of his DICE model to determine the "optimal" time-indexed carbon tax, starting at $42 per ton (of carbon, not ton of CO_2) in 2015 and rising to $217 per ton in the year 2105. In the present paper, I document several weaknesses in Nordhaus' standard case for a carbon tax, including his unduly pessimistic estimates and the dangers of a poorly implemented policy. I conclude that economists should reexamine several key issues before rushing to judgment on the need for government measures to combat global warming.

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I. Introduction

The 2007 Nobel Peace Prize awarded to Al Gore and the Intergovernmental Panel on Climate Change (IPCC) underscores the public's growing awareness and concern over anthropogenic (manmade) global warming. Many climatologists and other relevant scientists claim that emissions of greenhouse gases (GHGs) from human activity will lead to rising temperatures, which in turn will spell potentially catastrophic hardship for future generations. If this is true, then the economist will recognize what former Chief Economist of the World Bank Nicholas Stern described, in his famous report to the British government, as "the greatest example of market failure we have ever seen" (Stern 2007, p. 1).

With the science of global warming so stipulated, the standard reaction of most economists is to recommend a government policy to internalize the externality; the debate has largely revolved around the best mechanism (e.g. "cap and trade" versus a carbon tax) and the appropriate magnitude of the corrective penalty on carbon emissions. Although the most important implementation of emission curbs to date, the Kyoto Protocol, relies on tradable permits, a growing number of economists have concluded that a carbon tax can achieve a desired level of emissions more efficiently (e.g. Nordhaus 2007b, Pizer 1997). It would seem that the "consensus" in the natural sciences on anthropogenic global warming has carried over into the social sciences, with an emerging consensus on a carbon tax as the best way to balance present economic growth against future losses due to avoidable climate change. Indeed, as of this writing there is apparently not a single peer-reviewed economics article challenging the basic case for a carbon tax (while the above citations contain several criticisms of a cap and trade system).

The present paper argues that this consensus is unjustified, because the case for a carbon tax is much weaker than most economists are probably aware. We will illustrate the problems with a thorough analysis of the assumptions underlying William Nordhaus' DICE model, which is an excellent representative of the orthodox approach. We will first document that *each* critical step in Nordhaus' case relies on numerical estimates that are quite uncertain, and to which the magnitude of the "optimal" carbon tax may be very sensitive. After this immanent critique, we will examine some of the drawbacks of real-world government action to assess the danger of Nordhaus' approach.

The paper is organized as follows: Section II provides a summary of the DICE model and IPCC Fourth Assessment Report to which it is calibrated. Section III documents the large uncertainty in each of the important steps in Nordhaus' argument for a carbon tax. Section IV contrasts theoretical government solutions with real-world market approaches. Section V concludes.

II. Summary of the DICE Model and the IPCC Fourth Assessment Report

Before closely examining the potential problems of Nordhaus' case for a carbon tax, this section provides a quick overview of his DICE model, and the IPCC scientific analysis to which Nordhaus' economics is anchored.

Nordhaus and the DICE Model

A professor at Yale University since 1967, William Nordhaus has been chosen as the representative of the mainstream in climate change economics for his longstanding career in an area in which he literally wrote the book (e.g. originally Nordhaus 1979 and more definitively Nordhaus 1994b). Although the criticisms of the present paper will be directed at Nordhaus, they will be relevant to most other proposals for a carbon tax as well.[1] As one expert put it: "A lot of economists interested in climate change start—and end—with Nordhaus."

[1] In contrast, the case for radical action on climate change offered by Nicholas Stern (2007) has met with serious criticism from the economics mainstream. See e.g. Dasgupta 2006, Gollier 2006, Mendelsohn 2006, Nordhaus 2007a, and Weitzman 2007a.

In the early 1990s, Nordhaus and collaborators developed the earliest versions of the RICE (Regional dynamic Integrated model of Climate and the Economy) and the aggregated DICE (Dynamic Integrated model of Climate and the Economy) models. The models have constantly evolved over time, benefiting from revised estimates from the natural sciences as well as structural improvements. Nordhaus and Boyer 2000 describes the RICE and DICE models as of 1999, while Nordhaus 2007b (which serves as the reference for the present paper) describes the DICE model as of September 2007. For a brief description of the mechanics of the model, we turn to Nordhaus himself:

> The DICE model views the economics of climate change from the perspective of neoclassical economic growth theory….The DICE model extends this approach by including the "natural capital" of the climate system as an additional kind of capital stock. In other words, we can view concentrations of GHGs as negative natural capital, and emissions reductions as investments that raise the quantity of natural capital. By devoting output to emissions reductions, economies reduce consumption today but prevent economically harmful climate change and thereby increase consumption possibilities in the future…
>
> In the DICE model, the world is assumed to have a well-defined set of preferences, represented by a "social welfare function," which ranks different paths of consumption….The relative importance of different generations is affected by two central normative parameters: the pure rate of time preference and the elasticity of the marginal utility of consumption….In the modeling, we set the parameters to be consistent with observed economic outcomes as reflected by interest rates and rates of return on capital…
>
> Output is produced with a Cobb-Douglas production function in capital, labor, and energy. Energy takes the form of either carbon-based fuels (such as coal) or non-carbon-based technologies (such as solar or geothermal energy or nuclear power). Technological change takes two forms: economy-wide technological change and carbon-saving technological change. Carbon-saving technological change is modeled as reducing the ratio of CO_2 emissions to output. Carbon fuels are limited in supply. Substitution from carbon to noncarbon fuels takes place over time as carbon-based fuels become more expensive, either because of resource exhaustion or because policies are taken to limit carbon emissions. (Nordhaus 2007b, pp. 29-30)

Ultimately, the DICE model yields a large matrix of output, describing the trajectories (in ten-year increments) of variables such as total global emissions, the damages from climate change, the social cost of carbon, and the optimal tax on carbon (expressed as 2005 dollars per ton).

The Intergovernmental Panel on Climate Change Fourth Assessment Report

The Intergovernmental Panel on Climate Change (IPCC) is the world authority on climate change science. The IPCC was established by the World Meteorological Organization and the United Nations Environment Programme in 1988. Its periodic reports do not contain new research, but instead "make policy-relevant—as opposed to policy-prescriptive—assessments of the existing worldwide literature on the scientific, technical and socio-economic aspects of climate change" (IPCC 2007, p. v). Working Group I's contribution, "The Physical Science Basis," to the Fourth Assessment Report (abbreviated as AR4) contains chapters "written by 152 coordinating lead authors and lead authors from over 30 countries and reviewed by over 600 experts" (IPCC 2007, p. v).

The IPCC AR4 report is the best single repository for the natural science relationships to which Nordhaus calibrates the DICE model. The basic story of the IPCC AR4 is that human activities are emitting CO_2 and other greenhouse gases, which allow sunlight to pass through them but trap some of the lower-frequency infrared radiation that the earth emits back to the atmosphere. This "enhanced greenhouse effect" leads to global warming, which many scientists and economists warn will have dramatic impacts on human well-being over the next several hundred years.

III. Weaknesses in the DICE Model's Recommended Carbon Tax Profile

Nordhaus' method for calculating the optimal carbon tax (as a function of time) is straightforward. He assumes that economic activity releases greenhouse gases (GHGs), thereby raising the concentration of GHGs in the atmosphere. The increased concentration leads to higher temperatures, which in turn cause net economic damages to future generations. Because the present generation is assumed to care about the welfare of its descendants, the emission of the marginal ton of carbon into the atmosphere today translates into a (discounted) loss in present utility. Market prices do not fully reflect this aspect of the situation, and so (Nordhaus concludes) a Pigovian tax on carbon usage is justified. For economic efficiency, the tax should just compensate for the present discounted value of the reduction in future utility flows due to the higher warming caused by the marginal emission.

The calibrated ideal tax (which varies over time) is naturally quite dependent on the numerical estimates undergirding the DICE model. Yet as we shall see, every step in the argument above relies on estimates with much uncertainty. Therefore, even accepting the basic premise of the argument for a carbon tax, mainstream economists should be quite hesitant to clamor for its implementation. In the remainder of this section, we summarize these key areas.

Uncertainty Area #1: Future GHG Atmospheric Concentrations May Be Overstated

Unlike some other negative externalities, the impact of a given quantity of GHG emissions is crucially dependent on the concentration already in the atmosphere. Therefore, an efficient carbon tax regime must incorporate projections of future GHG concentrations as a function both of time and the taxes themselves. Yet these projections are not as straightforward as one might think. A major source of uncertainty concerns carbon "sinks," such as the oceans. As humans pump tons of carbon dioxide into the atmosphere, some of it is absorbed by the oceans. This mitigates the growth in atmospheric GHG concentrations, and hence reduces the projected damages from a given amount of emissions. The problem for modelers is that the oceans are vast but *finite* sinks. In response to critics of his earlier versions, Nordhaus explicitly adopted a "three reservoir" model of carbon flows in his 1999 and subsequent versions of DICE (Nordhaus and

Boyer 2000, p. 57). By its very nature, this particular model cannot be simply calibrated with historical measurements on carbon concentrations, because the oceans are not yet saturated.

The critics of the earlier versions of Nordhaus' model certainly had a point: It would be too optimistic to rely solely on historical correlations of emissions with atmospheric concentrations, because once the oceans "fill up," further emissions will cause atmospheric concentrations to grow at a faster rate than they had in the past. On the other hand, once we leave the realm of empirical trends, the projections become quite tenuous. The current parameterization of DICE's three reservoir model of carbon flow may be revised significantly in the coming years.

Uncertainty Area #2: Temperature Increase from a Given GHG Concentration May Be Overstated

The next step in Nordhaus' argument—namely, that higher GHG concentrations will lead to higher global temperatures, what is termed *climate sensitivity*—is also fraught with uncertainty once we attempt specific numerical estimates. The major controversy here is how to handle *feedback effects*.

There is truly a consensus on the *direct* temperature increase from higher CO_2 concentrations. If these concentrations double (relative to preindustrial times, with a benchmark year of 1750), global mean surface temperatures will rise around 1.2˚C (IPCC 2007, p. 631). Yet the IPCC AR4 assessment says that a doubling will lead to an "equilibrium" (i.e. long run[2]) temperature increase that is "likely"[3] in the range of 2 to 4.5˚C, with a best guess of 3˚C (IPCC 2007, p. 799). The range of estimates is significantly higher than the direct effect, because it is assumed that

[2] Note that the equilibrium climate sensitivity does *not* refer to the higher global mean surface air temperature that would obtain at the moment atmospheric concentrations reached a doubling point. Rather, the equilibrium sensitivity allows for the CO_2 doubling to work out all of its long run (feedback) effects.
[3] In the AR4 report, the word *likely* has the specific meaning of "above 66%."

temperature rises themselves will set into motion further warming. For example, as the earth warms due to GHG emissions, the atmosphere will hold more water vapor, which in turn will enhance the greenhouse effect. Note that it is this most recent best guess of 3˚C that Nordhaus plugs into DICE-2007, in order to compute the optimal carbon tax profile.

The relatively large spread among estimates of this climate sensitivity parameter is due to honest disagreements over how to model such feedback effects. To give a flavor of the uncertainties, consider the following discussion of modeling clouds from the latest IPCC report:

> In spite of this undeniable progress, the amplitude and **even the sign** of cloud feedbacks was noted in the TAR [Third Assessment Report, released in 2001—RPM] as highly uncertain, and this uncertainty was cited as one of the key factors explaining the spread in model simulations of future climate for a given emission scenario…
>
> The importance of simulated cloud feedbacks was revealed by the analysis of model results…and the first extensive model intercomparisons…also showed a substantial model dependency. The strong effect of cloud processes on climate model sensitivities to greenhouse gases was emphasized further through a now-classic set of General Circulation Model (GCM) experiments, carried out by Senior and Mitchell…They produced global average surface temperature changes (due to doubled atmospheric CO_2 concentration) ranging from 1.9˚C to 5.4˚C, simply by altering the way that cloud radiative properties were treated in the model. It is somewhat unsettling that the results of a complex climate model can be so drastically altered by substituting one reasonable cloud parameterization for another, thereby approximately replicating the overall intermodal range of sensitivities. (IPCC 2007, p. 114, **bold** added)

When it comes to assigning a value for the sensitivity of global temperatures to increased GHG concentrations, we encounter the same methodological problem noted earlier. The climate sensitivities used in the models upon which Nordhaus relies are far more pessimistic than historical trends. From the preindustrial benchmark date until 2005, atmospheric CO_2 concentrations increased some 35 percent (from about 280 ppm to 379 ppm), while temperatures increased around 0.7˚C. Now if the relationship between CO_2 concentrations and global warming were linear, these observed values would yield a "revealed" climate sensitivity of about 2˚C, i.e. the very bottom of the IPCC's latest range. However, the IPCC reports that CO_2 concentrations have a *logarithmic* (not linear) relationship with their impact on the climate system (IPCC 2007, p. 140), and so the observed data points yield a climate sensitivity well below the IPCC's reported range.

The defender of the IPCC results would have some obvious objections to the above demonstration. First and most important, the climate sensitivity estimate of 3˚C for a doubling of CO_2 is a *long run* equilibrium concept; even if concentrations were immediately stabilized at today's value, the globe could continue to warm, justifying the (higher) estimated sensitivity. Moreover, in actual history there were other changes to the atmosphere besides the addition of CO_2; there were increases in other GHGs, as well as changes in solar radiation, volcanic eruptions, etc. To fairly isolate how much of the climate models' reported sensitivities are borne out by historical trends, versus how much they rely on expected future movements in temperature, it would be much better to focus on the sum of *all* radiative forcings[4] (not just those from increasing CO_2 concentrations) tabulated by the IPCC. This historical figure could then be compared with the radiative forcing caused by a hypothetical doubling of CO_2 (holding all else

[4] *Radiative forcing* is formally defined as "the change in net (down minus up) irradiance (solar plus longwave; in W m^{-2}) at the tropopause [the boundary between the troposphere, where most weather occurs, and the stratosphere, the next atmospheric layer above—RPM] after allowing for stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values" (IPCC 2007, p. 133). This rather opaque definition is necessary to resolve ambiguities for the actual calculation, but in layman's terms, radiative forcing is a measure of how much extra energy goes into (or out of) the climate system because of a given mechanism, such as GHG concentrations or volcanic eruptions. The higher the forcing, the more energy that is retained within the system, which leads to increased temperatures.

constant),[5] in order to more fairly contrast the historical record with the IPCC models' implied climate sensitivities. We next perform these calculations.

The IPCC AR4 reports a best guess of +1.6 W m^{-2} as the total radiative forcing from all changes, both anthropogenic and natural (solar activity and aerosols from volcanic eruptions), from preindustrial times through the year 2005 (p. 205). Again, this estimated total forcing went hand in hand with an observed temperature increase of 0.7˚C. Now a hypothetical doubling of CO_2, holding all other forcing mechanisms constant at preindustrial values, would yield a forcing of +3.7 W m^{-2} (IPCC 2007, p. 140). Unlike the case of CO_2 concentrations, when it comes to radiative forcings, there is an assumed linear relationship with global temperature increases (IPCC 2007, p. 197). Therefore, the observed temperature increase and calculated total radiative forcing, from preindustrial time through 2005, yields an observed climate sensitivity thus far of 1.6˚C, a little over half of the official best guess of 3˚C (the value Nordhaus uses in DICE-2007).

Our point here is not to suggest that the various climate modelers are demonstrably wrong. On the contrary, their simulations are consistent with the historical data, and in fact have been calibrated such that a strong graphical case can be made that anthropogenic influences are necessary to explain the observed warming of the 20th century (IPCC 2007, p. 684). Rather than claiming falsification, instead we are merely pointing out that the simulated response of global temperatures to GHG emissions have not *yet* played out according to IPCC estimates. The reported best guess of 3˚C warming from a doubling of CO_2 concentrations relies on feedback effects that, according the IPCC models, have not yet fully manifested themselves and/or were

[5] Strictly speaking, even this comparison would not be perfect, because the radiative forcing from one mechanism does not necessarily lead to the same (global mean surface) temperature increase. The concept here is *efficacy* (IPCC 2007, p. 197). Yet even the IPCC does not weight mechanisms by their efficacies, in its measure of cumulative forcing. This is partly because of the uncertainties involved, and also because the best estimates show other mechanisms to have efficacies comparable (generally within 25 percent below or above) to that of CO_2.

offset by other factors through the year 2005. It is still entirely plausible, therefore, that future climatologists will substantially revise their estimate of climate sensitivity, because presumed feedbacks and offsetting factors are not currently being modeled correctly.[6] The point we wish to drive home to economists is that the IPCC estimate of climate sensitivity is *not* akin to measuring the price elasticity of demand for potatoes. Rather, it is more analogous to predicting the impact on long run real GDP from a sudden doubling of the money supply. *This* type of task would yield a range of estimates from economists depending on the modeling approach, and the results would be much more susceptible to future revision, compared to a task requiring merely a straightforward measurement.

Uncertainty Area #3: Economic Damages from a Given Temperature Increase May Be Overstated

We come to the last major step in Nordhaus' argument, going from a given temperature increase to quantitative damages (measured in money). This crucial step is necessary to set the appropriate carbon tax, but it too rests on a surprisingly fragile foundation.

Nordhaus' basic approach is to estimate the damages in major sectors (such as agriculture, coastal regions, etc.) in order to come up with a percentage of GDP lost to global warming for stipulated increases in temperature. There is a broad range of such estimates, and Nordhaus sensibly relies on a mixture of their findings, rather than selecting one particular estimate. The problem here is that the more pessimistic estimates commit serious methodological errors that bias their results, and they consequently likely overstate the damage from a given amount of warming.

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[6] For example, Chylek and Lohmann (2008) points to a climate sensitivity on the low end of the AR4 range. Spencer et al.'s (2007) study of intraseasonal variations in tropical systems is even more radical. Their analysis suggests that increasing temperatures may lead to fewer ice clouds, which allows more longwave radiation to leave the atmosphere, thus providing a potential negative feedback ignored by current climate models.

The following Table 1 reproduces Nordhaus and Boyer's Table 4.11 (2000, p. 97), where they compare their own damage estimates to the United States[7] (for a warming of 2.5˚C) with those of other studies. Note that negative numbers imply benefits.

Table 1
Comparison of recent impact studies for 2.5˚C warming in United States
(Reproduced from Nordhaus and Boyer 2000, p. 97)

	Fankhauser 1995	Tol 1995	Mendelsohn and Neumann 1999	This study [i.e. Nordhaus and Boyer 2000]
Sector				
Market impacts				
Agriculture	8	10	-11	4
Energy	8	na	3	0
Sea level	9	9	0	6
Timber	1	na	-3	0
Water	16	na	4	0
Total market	42	19	-8	11
Nonmarket impacts				
Health, water quality, and human life	19	37	6	1
Migration	1	1	Na	Na
Human amenity, recreation and nonmarket time	na	12	-4	-17

[7] Of course, the ultimate issue is how much damage will be inflicted on the entire globe, not just the United States. But the best studies focus on the U.S., especially at the time of Nordhaus and Boyer 2000. Moreover, Mendelsohn reports (in response to an email inquiry) that his current work for the globe is thus far consistent with net damages not occurring until a temperature rise of more than 2 to 2.5˚C.

Species loss	8	5	Na	Na
Human settlements	na	Na	Na	6
Extreme and catastrophic events	0	0	Na	25
Total nonmarket	28	56	2	17
Total (market and nonmarket sectors)				
Billions of 1990 $	70	74	-7	28
% of GDP	1.3	1.5	-0.1	0.5

If one doesn't delve into the specifics of each study, it would appear that the damage estimates of Nordhaus (and Boyer) are quite reasonable, since they generally fall within the range of other reputable studies. However, as mentioned above, there is good reason to prefer the findings of Mendelsohn and Neumann over the others, since these authors correct some of the biases of earlier studies. In a short pamphlet Mendelsohn explains some of the flaws with previous studies:

> Daily mortality studies show that large increases in death among the elderly follow early summer heat waves…The studies were used to argue that warming would increase heat-stress deaths by from 6,000 to 9,800 per year in the United States alone…Analyses of annual mortality rates, however, show that the elderly live longer in warmer climates…A closer examination of heat-stress deaths reveals that they are higher in cold parts of the United States with high seasonal temperature variability. The death rates are relatively low in stable warm climates. Thus, heat-stress deaths appear to be caused not by warming but by temperature variability. (Mendelsohn 1999, p. 9)

> Crop research stations…are usually located near where that crop grows best. For example, the station could be at the optimum location for wheat…Moving to warmer temperatures will harm wheat productivity at that research station. [Some previous] simulation models [would] assume

> that warming reduces productivity across the landscape by that same amount. However, for farms that are cooler than the optimum, warming could actually increase productivity. So the farm in the optimal location is not likely to be representative of the effects across the landscape. (Mendelsohn 1999, pp. 10-11)

> [New agro-economic models involving adaptation] reveal that farmers can make adjustments in their tilling, irrigation, planting, and harvesting decisions that significantly reduce the damages from warming….Combining the effects of adaptation and carbon fertilization suggests that agriculture in the United States will benefit from warming… (Mendelsohn 1999, p. 14)

> Previous studies examined the rise in sea level as though it happened all at once. In fact, it is predicted to occur gradually over a century. By carefully timing our responses to match the needs in each decade, the costs of coping with sea-level rise could be spread across a century… (Mendelsohn 1999, p. 19)

> [E]arly studies on recreation examined only skiing. Warming leads to skiing damages because it shortens the skiing season and reduces the areas that remain suitable for skiing. But most outdoor recreation is based on warm weather. The increase in recreation opportunities that would result from the extension of warm weather overwhelms the reduction that would occur in winter-recreation opportunities… (Mendelsohn 1999, pp. 21-22)

Presumably, most readers will agree that Mendelsohn's favored studies (and in particular the ones he and co-author Neumann commissioned for their 1999 collection) are more trustworthy than some of the more pessimistic ones in their respective sectors. Consequently Nordhaus' own damage estimates, generally falling in the middle of these disparate studies, may be too high.[8]

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[8] Unlike DICE-1999, the damage function in DICE-2007 shows that *any* temperature increase, no matter how small, leads to net economic damages. This implies that the earth is either currently at its optimum temperature, or that a global cooling would yield net benefits. We make this elementary point because some analysts seem to think that any climate change (whether natural or anthropogenic) is detrimental.

In any event, the most serious difficulty with Nordhaus' damage estimates is how strongly they rely on the impacts from so-called catastrophic outcomes, defined as an indefinitely long loss of at least 25 percent of global GDP. In other words, in addition to the specific and carefully studied impacts of global warming on agriculture, recreation, etc., Nordhaus also wants to deal with the possibility of, say, the thermohaline circulation (the circulation of heat and salt among the world's oceans) completely shutting down. Yet rather than explicitly modeling various catastrophic scenarios and assessing their impact (as well as their likelihood), Nordhaus (with Boyer) instead relies on a survey of experts, as they explain here:

> There are many concerns about catastrophic impacts of climate change. Among the potential severe events are a sharp rise in sea level, shifting monsoons, a runaway greenhouse effect, collapse of the West Antarctic Ice Sheet, and changing ocean currents that would have a major cooling effect on some subregions, such as OECD Europe.
>
> To judge the importance of catastrophic impacts of climate change, a survey of experts pose [sic—RPM] the following questions:
>
> > Some people are concerned about a low-probability, high-consequence output of climate change. Assume by "high-consequence" we mean a 25 percent loss of global income indefinitely, which is approximately the loss in output during the Great Depression. (a) What is the probability of such a high-consequence outcome for scenario A, i.e., if the warming is 3 degrees C in 2090 as described above? (b) What is the probability of such a high-consequence outcome for scenario B, i.e., if the warming is 6 degrees C in 2175 as described above? (c) What is the probability of such a high-consequence outcome for scenario C, i.e., if the warming is 6 degrees in 2090 as described above?[9]
>
> The respondents showed greater relative concern about the large-temperature-increase and rapid-temperature-increase scenarios. The mean (median) probability of extremely unfavorable impacts was 0.6 (0.5) percent for the 3-degrees-C-in-a-century scenario A and 3.4 (2.0) percent for

[9] Here the authors insert a footnote, citing Nordhaus (1994) as the source of the survey text.

scenario B. The assessment of the catastrophic scenarios varied greatly across respondents and particularly across disciplines. (Nordhaus and Boyer 2000, p. 87)

After describing his survey and the mean (median) probabilities for catastrophic loss under the three warming scenarios, Nordhaus (and Boyer) then write, "Developments since the survey above have heightened concerns about the risks associated with major geophysical changes, particularly those associated with potential changes in thermohaline circulation" (p. 87). They cite various research that makes these concerns more dire, and conclude, "Although much further work needs to be done in this area, it does suggest that the risk of major impacts rises sharply as temperature increases beyond the 2 to 3˚C range" (p. 88).

At this point, Nordhaus and Boyer wish to alter the estimates provided by the respondents to the original 1994 survey (given in the block quotation above). Yet instead of freshly polling the experts and calculating the new set of mean and median probabilities for the various warming scenarios, Nordhaus and Boyer simply adjust the original numbers in the following manner:

> To reflect these growing concerns, **we assume the probability of a catastrophe with 2.5˚C warming is double the estimated probability for a 3˚C warming from the survey, that the probability associated with a 6˚C warming is double the survey estimate, and that the percentage of global income lost in a catastrophe is 20 percent higher than the figure quoted in the survey**. This implies that the probability of a catastrophic impact is 1.2 percent with a 2.5˚C warming and 6.8 percent with a 6˚C warming. (Nordhaus and Boyer 2000, p. 88, **bold** added)

These are rather bold changes. To paraphrase: Nordhaus in 1994 asked experts to estimate (among other things) the probability of global GDP loss of 25 percent in the event of 3˚C warming. The surveyed experts gave him their answers, from which he computed the mean. By

1999, further research had made these scenarios seem more plausible and/or catastrophic. So Nordhaus (and Boyer) took the original average of probabilities reported by the experts, *doubled it*, and then assigned this as the probability for a *30 percent loss of GDP rather than the 25 percent* the experts had been told to consider, for a less significant *warming of 2.5˚C rather than the 3˚C* mentioned in the original survey.[10] Interestingly, more recent research suggests that at least some of these catastrophic scenarios were false alarms.[11]

The reason we have spent so much space documenting the source of these estimates is that (at least in the 1999 version of Nordhaus' model) they constitute the *majority* of the damages from climate change. The following Table 2 reproduces (portions of) Table 4.10 from Nordhaus and Boyer (2000, p. 91), which summarize the sectoral impacts of a 2.5˚C warming.

[10] In fairness to Nordhaus and Boyer, convenience apparently guided some of these choices. For example, at the time of writing their (2000) book, the scientific consensus was that a benchmark doubling would lead to a 2.5˚C warming, and so this is presumably why they adjusted the temperature threshold down from 3˚C as the original survey had indicated.

[11] According to the latest IPCC AR4: "Abrupt climate changes, such as the collapse of the West Antarctic Ice Sheet, the rapid loss of the Greenland Ice Sheet or large-scale changes of ocean circulation systems, are not considered likely to occur in the 21st century, based on currently available model results. However, the occurrence of such changes becomes increasingly more likely as the perturbation of the climate system progresses" (p. 818). A 2006 *Science* article (Kerr 2006) was entitled, "Global Climate Change—False Alarm: Atlantic Conveyor Belt Hasn't Slowed Down After All," as explained in Lomborg (2007).

Table 2
Summary of Sectoral Impacts in Nordhaus' 1999 Approach
(Partial Reproduction of Table 4.10 of Nordhaus and Boyer 2000, p. 91)

	Total (2.5°C)	Agriculture	Other vulnerable market	Coastal	Health	Nonmarket time use	Settlements	Catastrophic impact (2.5°C)
United States	0.45	0.06	0.00	0.11	0.02	-0.28	0.10	0.44
China	0.22	-0.37	0.13	0.07	0.09	-0.26	0.05	0.52
Japan	0.50	-0.46	0.00	0.56	0.02	-0.31	0.25	0.45
OECD Europe	2.83	0.49	0.00	0.60	0.02	-0.43	0.25	1.91
Russia	-0.65	-0.69	-0.37	0.09	0.02	-0.75	0.05	0.99
India	4.93	1.08	0.40	0.09	0.69	0.30	0.10	2.27
Africa	3.91	0.05	0.09	0.02	3.00	0.25	0.10	0.39
Global (output weighted)	**1.50**	0.13	0.05	0.32	0.10	-0.29	0.17	**1.02**

As Table 2 indicates, the global damages (weighted by the output in each region) from 2.5˚C warming are estimated at 1.50 percent of GDP, yet 1.02 percent of GDP loss (i.e. 68 percent of total damages) is due to the "catastrophic impact" scenarios described earlier.[12] Inasmuch as this particular sectoral impact was not derived in a rigorous way, it is quite possible that it vastly overestimates the damages from present carbon emissions.

Summing Up: The Optimal Carbon Tax Based on Conservative Estimates

To give the reader a sense of the quantitative significance of the uncertainties discussed in this section, we can modify the latest version of Nordhaus' DICE model and observe the effect on its recommended carbon tax profile. In particular, we will run Nordhaus' DICE model after removing the poorly derived "catastrophic impact" component (such that world output-weighted GDP loss is 0.48 percent from a 2.5˚C warming)[13] and returning the estimate of climate sensitivity from 3.0˚C down to 2.5˚C.[14] These two changes drastically affect the "optimal" carbon tax for a given year:

Table 3
DICE Model Optimal Carbon Tax
Original vs. Adjusted Values

	2015	2025	2035	2045	2055	2065	2075
Nordhaus 2007b	$41.90	$53.39	$66.48	$81.31	$98.00	$116.77	$137.82
Adjusted	$9.46	$12.02	$14.94	$18.23	$21.91	$26.03	$30.62

[12] Strictly speaking, these figures reflect the amount of output society is willing to pay to avoid the risks of catastrophic climate change. Because of risk aversion, the figures are higher than the actuarially "fair" amount of damage to assign to these unlikely yet catastrophic outcomes. In the text we have omitted this subtlety because Nordhaus 2007b drops the "willingness to pay" approach to damage estimates, and deals with risk aversion directly.

[13] Of course the complete removal of catastrophic impacts is unjustified. We do so merely to show how much of Nordhaus' optimal tax is due to this sector (as well as a climate sensitivity of 3.0˚C rather than 2.5˚C).

[14] For those familiar with the model, we reduced T2XCO2 from 3.0 to 2.5, and reduced A2 from 0.0028388 to 0.000768.

As Table 3 indicates, the uncertainties discussed in this section can drastically affect the magnitude of the economically efficient Pigovian tax on carbon. Naturally, the proponent of strict measures could argue that Nordhaus may be *underestimating* the risks of inaction. Although certainly possible, we believe the balance of evidence lies in the favor of conservatism, since we have identified several key areas in which Nordhaus relies on speculative estimates that depart from historical trends in a direction that yields higher carbon taxes.

IV. Idealized Government Solutions versus Practical Market Solutions

Thus far in the paper we have focused on technical criticisms of Nordhaus' calculation of the optimal carbon tax profile. Yet these arguments, though important, may divert economists from the most serious dangers of a massive new carbon taxation program. To put it succinctly, Nordhaus' proposal—and others like it—are overly optimistic about the potency of government regulation, and unduly pessimistic about the creative responses of a market economy. Those calling for a carbon tax focus on market failure but ignore the possibility of government failure.

The Wrong Climate Goal Can Yield Enormous Net Costs

DICE-2007 contains simulations not just of the baseline (no controls) and the optimal carbon tax scenarios, but of many other policies as well. The results show that the dangers from an overly ambitious and/or inefficiently structured policy can swamp the potential benefits of a perfectly calibrated and efficiently targeted one (i.e. the optimal carbon tax scenario). As Table 4 indicates, Nordhaus' optimal plan yields net benefits of some \$3 trillion (consisting of \$5 trillion in reduced climatic damages and \$2 trillion of abatement costs). Yet some of the other popular proposals have abatement costs that exceed their benefits. The worst is Gore's 2007 proposal to reduce CO_2 emissions 90 percent by 2050; DICE-2007 estimated this plan would make the world more than \$21 trillion poorer than if there were no controls on carbon.

Table 4
DICE's Relative Benefits of Different Climate Policies
(trillions of 2005 US $, adapted from Nordhaus 2007b, p. 160)

Climate Policy	PDV Difference from Baseline	PDV of Environmental Damages	PDV of Abatement Costs	Sum of Damages and Costs
No controls baseline	0.00	22.55	0.04	22.59
Optimal tax	+3.07	17.31	2.20	19.52
Limit CO_2 to 560 ppm	+2.67	15.97	3.95	19.92
Kyoto with US	+0.63	21.38	0.58	21.96
Kyoto without US	+0.10	22.43	0.07	22.49
Stern Review discount rate	-14.18	9.02	27.74	36.77
Limit temp. to 1.5˚C	-14.44	9.95	27.08	37.03
Limit CO_2 to 420 ppm	-14.60	9.95	27.24	37.19
Gore's 90% emissions cut	-21.36	10.05	33.90	43.96

Some comments on Table 4 are in order. The optimal carbon tax is the best policy for two related reasons: first, it is calibrated to balance marginal abatement costs against marginal benefits from avoided climatic damage; and second, it uses a very flexible tool (namely, time-varying penalties on carbon use) that can be perfectly correlated (in the DICE model, at least) with the level of damages inflicted on the world. In contrast, the Gore proposal is disastrous because it fails on both counts. First, its ambitious reductions in environmental damage are achieved at a price that exceeds the benefits. Second, by choosing a somewhat arbitrary and blunt tool (namely, a reduction in emissions by a certain date), this aggressive containment of environmental damages is achieved at a higher cost than necessary. For example, if Gore had instead proposed to limit CO_2 concentrations to 1.5 times their preindustrial value (i.e. 420 ppm), then abatement costs *and* environmental damages would both be lower than what his emissions reduction would achieve.

In a cost-benefit approach to climate policy, the variable of ultimate concern is the damage inflicted on humans from a changing climate. In the DICE model (and presumably in the real world), this damage can be directly traced back to a given amount of warming, which in turn can be traced back to CO_2 concentrations, and then to emissions. A blunt policy which cannot vary over time (unlike the carbon tax) will be worse, the further along this chain of causality it focuses its attention.

We can illustrate this principle by comparing the policy of limiting CO_2 to 420 ppm, versus the policy of limiting temperature increases to 1.5˚C. As Table 4 above indicates, both policies have roughly the same benefits in terms of reduced environmental damage, but the former policy has $160 billion in higher abatement costs. Ironically, the policy that focuses on atmospheric concentrations actually allows *greater* global warming than the (lower abatement cost) strategy of focusing directly on temperature. As Table 5 below explains, this paradoxical outcome occurs because CO_2 concentrations in the temperature policy briefly shoot above the 420 ppm threshold, but come back down in order to contain temperature increases. Thus, the crude rule that forbids CO_2 concentrations from ever crossing this threshold imposes abatement costs with no corresponding environmental benefit (at least in the DICE model).

Table 5
Arbitrary Climate Goals Impose Unnecessary Abatement Costs
(Adapted from Tables V-7 and V-8, Nordhaus 2007b, pp. 166-167)

Strategy and Variable	2005	2015	2025	2050	2100	2200
Limit to 420ppm						
CO_2 conc. (ppm)	379.8	405.2	415.1	420.2	420.2	420.2
Temp. increase (˚C)	0.73	0.94	1.10	1.36	1.61	1.78
Limit to 1.5˚C						
CO_2 conc. (ppm)	379.8	405.2	418.2	**434.4**	**400.4**	**388.2**
Temp. increase (˚C)	0.73	0.94	1.12	1.43	1.50	1.50

The lesson from Table 5 is clear: Arbitrary constraints on carbon emissions can lead to unnecessary abatement costs, even from the point of view of achieving a desired climate change objective. To repeat, in the DICE model, imposing a cap of 420 ppm costs more (in terms of forfeited production) than limiting temperature increases to 1.5˚C, *and* the former constraint leads to more global warming. Thus, it is a poor policy even if we believe that mitigating climate change possesses its own intrinsic value, besides the avoided economic impact on humans.

Unfortunately, many of the politically popular proposals in this arena are of just this form. Not only do they fail to match increments in avoided climate change with the corresponding opportunity costs in terms of foregone emissions, but these proposals typically fail to achieve their aggressive environmental objectives in the least costly manner. (In other words, even if we are going to buy more environmental benefits than we ought to, we should still shop for the best price.) Recall that the incredibly costly proposals laid out in Table 4 above were not interesting thought experiments invented by Nordhaus. On the contrary, these were inspired by actual proposals being seriously discussed by policymakers, including the Stern Review and Gore proposals, with their net costs of more than $14 and $21 trillion, respectively.

<u>Policies Will Not Be Implemented in Textbook Fashion</u>

The figures in Table 4 refer to idealized, textbook implementation of the various policies—even the inefficient ones. In reality, whether the program is a carbon tax, cap and trade scheme, or some other regime of controls and regulations, there will always be governments that do not strictly enforce its provisions. Although we are all living on one planet, different regions will be affected in different ways from climate change as well as from efforts to limit carbon emissions. For example, Russia has much less to lose from global warming than Egypt, while a return to 1990 emissions levels would imply a much higher loss of potential income for the people of

China than the people of Switzerland. Because of their different circumstances, some countries may opt out of a proposed climate change program altogether, or (more likely) they will nominally participate while exempting favored sectors. In order to achieve the estimated benefits in Table 4, the "good" proposals must be enforced not only a worldwide scale, but also nonstop for centuries. If there is a severe recession in 2040, for example, and much of the world relaxes its carbon restraints, then a large portion of the net benefits from a "good" policy could be forfeited.

Nordhaus himself addresses this issue by running the DICE model with varying levels of worldwide participation:

> Our modeling results point to the importance of near-universal participation in programs to reduce greenhouse gases. Because of the structure of the costs of abatement, with marginal costs being very low for the initial reductions but rising sharply for higher reductions, there are substantial excess costs if the preponderance of sectors and countries are not fully included. We preliminarily estimate that a participation rate of 50 percent, as compared to 100 percent, will impose an abatement-cost penalty of 250 percent. Even with the participation of the top 15 countries and regions, consisting of three-quarters of world emissions, we estimate that the cost penalty is about 70 percent. (Nordhaus 2007b, p. 20)

Before leaving this point, we should clarify Nordhaus' claims. He is saying that if only half of the world (weighted by current emission levels) is subject to the optimal tax regime, then *the sacrifice in welfare (measured in money) necessary to achieve a given environmental objective* will be 250 percent higher, relative to the cost under a regime of worldwide participation. (Notice that this does not necessarily mean that the optimal carbon tax in the participating countries will be 250 percent higher, relative to the full participation scenario.) For the truly interesting case, where large, carbon-intensive economies such as China and India do not participate, Nordhaus offers no estimates of the cost penalty.

Nordhaus is certainly not naïve when it comes to his idealized carbon tax and the actual rough-and-tumble of international politics. He warns the reader:

> It will be useful to provide a word of caution about the optimal case. This is not presented in the belief that an environmental czar will suddenly appear to provide infallible canons of policy that will be religiously followed by all. Rather, the optimal policy is provided as a benchmark to determine how efficient or inefficient alternative approaches may be. This is the *best possible* policy path for emissions reductions given the economic, technological, and geophysical constraints that we have estimated. (Nordhaus 2007b, p. 49, italics original)

Unfortunately, we would argue that Nordhaus is still overrating the virtues of his proposed carbon tax. It would be an exercise in unwarranted precision to assign probability distributions to the strategies in Table 4—or better yet, to the strategies in Table 4 after their costs have been multiplied by some factor to account for non-participation—and then to calculate the expected value of an uncertain climate change policy. Even so, the extreme waste of proposals such as Gore's, in contrast to the more modest net benefits of the theoretically ideal plan, underscore the danger. For an analogy, neoclassical models can certainly demonstrate conditions under which an "optimal tariff" enhances welfare. Yet if we were in an initial state of relatively free world trade, how many economists would lend support to massive new tariffs? What is the likelihood that politicians the world over would enact them according to the recommendations of theoretical economists, rather than for purposes of revenue or favors to domestic industries?

In this context, then, we ask economists to look before they leap into supporting a massive new global carbon tax (or other such scheme). There is a very real possibility that it would lead to the worst of both worlds, with worldwide production heavily distorted due to uneven levels and enforcement of emissions controls, yet with total emissions still in line to cause severe climate change damages according to the scientific computer simulations.

Economic Growth Is Not a "Do-Nothing" Approach

Although it is not politically popular, a very robust approach to climate change is reliance on economic growth. Whatever happens, humans will adapt more easily if they are wealthier. This adaptation includes obvious elements such as crop rotation, more extensive use of air conditioning, and fortification of coastal barriers. But it also includes more exotic possibilities, such as "geoengineering" solutions to the problem (placing mirrors in space, filling the atmosphere with aerosols to reflect sunlight, etc.). Ironically, government programs to avert global warming will undeniably stifle economic growth, thereby limiting the ability of people to adapt in such ways.[15]

It is true that in any formal model with a negative externality due to carbon emissions, the decentralized market outcome will be Pareto inefficient. However, by their very nature such models cannot incorporate the superior information that future generations will possess. By bequeathing them with a freer economy and more material wealth, we give them flexibility to deal with environmental challenges as they occur. Yes, in principle Nordhaus' optimal carbon tax could be entirely repealed in 2068 if a bioengineering solution presents itself, or if a commercially viable non-fossil fuel is developed; the uncertainty of the future shouldn't prevent us from always undertaking what appears to be the best option in the present. But in practice, this argument is dangerous, for massive new government programs would be quite difficult to unwind as new information becomes available.

[15] Bradley (2003, pp. 119-121) suggests a "no regrets" approach, where policy changes are made that both reduce GHG emissions and promote economic efficiency. These include congestion pricing for roads and the elimination of subsidies for energy use.

V. Conclusion

Many economists favor some form of government penalty on carbon dioxide emissions because of the threat of climate change. However, the steps in the argument—going from computer simulations to a specific, numerical tax on economic activity today—are riddled with uncertainties. On top of the theoretical difficulties, there is always the risk of politicians relying on politics—rather than pure science—to implement the recommended programs.

Rather than relying on conjectural models and the good faith of politicians, economists should instead consider the ability of markets to generate wealth to ease the adaptation process. Given the large uncertainties in each major step of the case for a carbon tax, we urge economists to reconsider their current support for such a policy.

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