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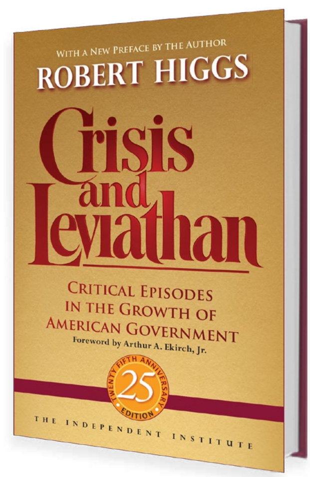

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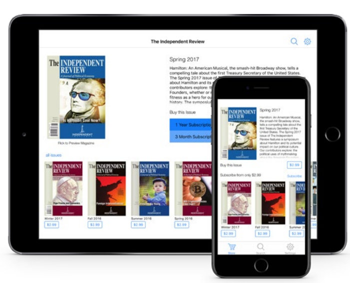

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Rolling the DICE

William Nordhaus's Dubious Case for a Carbon Tax

ROBERT P. MURPHY

The 2007 Nobel Peace Prize awarded to Al Gore and the Intergovernmental Panel on Climate Change (IPCC) underscores the public's growing awareness of and concern about anthropogenic (man-made) global warming. Many climatologists and other relevant scientists claim that emissions of greenhouse gases (GHGs) from human activity will lead to increases in the earth's temperature, which in turn will spell potentially catastrophic hardship for future generations. If this forecast proves to be accurate, economists will recognize what former World Bank chief economist Nicholas Stern described in his famous report to the British government as "the greatest example of market failure we have ever seen" (2007, 1).

With the science of global warming so stipulated, most economists' standard reaction is to recommend a government policy to internalize the externality; the debate has largely revolved around the best mechanism to deal with carbon emissions (for example, "cap and trade" versus a carbon tax) and the appropriate magnitude of the corrective penalty on emissions. Although the most important implementation of emission curbs to date, the Kyoto Protocol, relies on tradable permits, increasingly more economists have concluded that a carbon tax can achieve a desired level of emissions more efficiently (Pizer 1997; Nordhaus 2008). It would seem that the "consensus" in the natural sciences on anthropogenic global warming has carried over into the social sciences in the form of an emerging consensus on a carbon tax as

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the best way to balance present economic growth against future losses caused by avoidable climate change. Indeed, as of this writing, I am not aware of a single peer-reviewed economics article that challenges the basic case for a carbon tax (although the preceding citations contain several criticisms of a cap-and-trade system).

In this article, I argue that this consensus is unjustified because the case for a carbon tax is much weaker than most economists are probably aware. I illustrate the problems with a thorough analysis of the assumptions underlying William Nordhaus's Dynamic Integrated Model of Climate and the Economy (hereafter, "DICE model"), which is an excellent representative of the orthodox approach. I first document that *each* critical step in Nordhaus's 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, to assess the danger of Nordhaus' approach I examine some of the drawbacks of real-world government action.

Summary of the DICE Model and the IPCC Fourth Assessment Report

Before closely examining the potential problems of Nordhaus's case for a carbon tax, I provide in this section a quick overview of his DICE model and the IPCC scientific analysis to which his 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 (originally Nordhaus 1979 and more definitively Nordhaus 1994b). Although my criticisms are directed at Nordhaus, they are relevant to most other proposals for a carbon tax as well.[1] As one expert told me, "A lot of economists interested in climate change start—and end—with Nordhaus."

In the early 1990s, Nordhaus and his collaborators developed the earliest versions of the Regional Dynamic Integrated Model of Climate and the Economy (RICE) and the aggregated DICE models. These models have evolved over time, incorporating revised estimates from the natural sciences as well as structural improvements. Nordhaus and Boyer 2000 describes the RICE and DICE models as of 1999, and Nordhaus 2008 (which serves as the reference for the present article) describes the DICE model as of September 2007. For a brief description of the model's mechanics, we turn to Nordhaus himself:

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, for example, Dasgupta 2006, Gollier 2006, Mendelsohn 2006, Nordhaus 2007, and Weitzman 2007.

> 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 2008, 32–35)

The DICE model ultimately 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 IPCC Fourth Assessment Report

The IPCC is the world authority on climate-change science.[2] It was established by the World Meteorological Organization and the United Nations Environment

2. Many "skeptics" would strongly object to this characterization of the IPCC; see, for example, Singer and Avery 2007 and especially Solomon 2008. For the present article, I am not trying to challenge the basic scientific foundation of the case for man-made global climate change, but am instead pointing out that the case for *policy activism* (that is, a carbon tax) is much weaker than even the "consensus" scientific claims can support.

Program 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" (Jarraud and Steiner 2007, v). Working Group I's contribution to the *Fourth Assessment Report* (abbreviated *AR4*), *The Physical Science Basis,* contains chapters "written by 152 coordinating lead authors and lead authors from over 30 countries and reviewed by over 600 experts" (Jarraud and Steiner 2007, v).

The *AR4* is the best single repository for the natural-science relationships to which Nordhaus calibrates the DICE model. The basic story of the *AR4* is that human activities are emitting carbon dioxide (CO_2) and other GHGs, which allow sunlight to pass through them, but trap some of the lower-frequency infrared radiation that bounces back from Earth. This "enhanced greenhouse effect" leads to global warming, which many scientists and economists warn will have dramatic effects on human well-being over the next several hundred years.

Weaknesses in the DICE Model's Recommended Carbon Tax Profile

Nordhaus's method for calculating the optimal carbon tax (as a function of time) is straightforward. He assumes that economic activity releases GHGs, thereby raising their concentration 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 owing to the warming that the marginal emission will cause.

The calibrated ideal tax (which varies over time) depends on the numerical estimates undergirding the DICE model. Yet, as we shall see, every step in Nordhaus's argument relies on estimates subject to great uncertainty. Therefore, even if mainstream economists accept the argument's basic premise for a carbon tax, they should hesitate to clamor for implementation of the tax. In the remainder of this section, I summarize these key areas of uncertainty.

Uncertainty Area One: Future GHG Atmospheric Concentrations May Be Overstated

Unlike some other negative externalities, the impact of a given quantity of GHG emissions depends crucially on the concentration already in the atmosphere. Therefore, an efficient carbon tax regime must incorporate projections of future GHG concentrations as a function of time and of 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, the oceans absorb some of it. This absorption 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 earlier versions of his DICE model, Nordhaus explicitly adopted a "three-reservoir" model of carbon flows in his 1999 and subsequent versions (Nordhaus and Boyer 2000, 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's 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 did in the past. However, once we leave the realm of empirical trends, the projections become tenuous. The current parameterization of the three-reservoir DICE model of carbon flow may be revised significantly in the coming years.

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

The next step in Nordhaus's argument—namely, that higher GHG concentrations will lead to higher global temperatures, an effect termed *climate sensitivity*—is also fraught with uncertainty once we attempt to arrive at 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 approximately 1.2°C (Randall et al. 2007, 631). Yet the IPCC *AR4* says that a doubling will lead to an "equilibrium" (that is, long-run)[3] temperature increase that is "likely"[4] to be in the range of 2.0 to 4.5°C, with a best guess of 3.0°C (Meehl et al. 2007, 799). The range of estimates is significantly higher than the direct effect because it is assumed that temperature rises themselves will set into motion further warming. For example, as Earth warms due to GHG emissions, the atmosphere will hold more water vapor, which in turn will enhance the greenhouse effect. Note that Nordhaus plugs this most recent best guess of 3.0°C into DICE 2007 to compute the optimal carbon tax profile.

3. 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 reach a doubling point. Rather, the equilibrium sensitivity allows for the CO_2 doubling to work out all of its long-run (feedback) effects.

4. In the *AR4*, the word *likely* has the specific meaning of "higher than 66 percent."

The relatively large spread of the estimates of this climate-sensitivity parameter arises from honest disagreements over how to model such feedback effects. To gain a sense of these uncertainties, consider the following discussion of the modeling of cloud effects 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] 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. (Le Treut et al. 2007, 114, emphasis added)

In 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 on which Nordhaus relies are far more pessimistic than historical trends. From the preindustrial benchmark date until 2005, atmospheric CO_2 concentrations increased approximately 35 percent (from about 280 parts per million [ppm] to 379 ppm), and temperatures increased approximately 0.7°C. If the relationship between CO_2 concentrations and global warming were linear, these observed values would yield a "revealed" climate sensitivity of about 2.0°C—that is, a value at the very bottom of the IPCC's latest range. However, the IPCC reports that CO_2 concentrations have a *logarithmic* (not a linear) relationship in their impact on the climate system (Forster et al. 2007, 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 preceding demonstration. First, and most important, the climate-sensitivity estimate of 3.0°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 might continue to warm in accordance with the (higher) estimated sensitivity. Moreover, in actual history, the atmosphere underwent other changes besides the addition of CO_2, including increases in other GHGs, changes in solar radiation, volcanic eruptions, and so forth. To isolate fairly how much of the climate models' reported sensitivities is borne out by historical trends versus how much the models rely on expected future movements in temperature, it would be much better to focus on the sum of *all* radiative forcings[5] (not just on those from increasing CO_2 concentrations) tabulated by the IPCC. This historical figure can then be compared with the radiative forcing caused by a hypothetical doubling of CO_2 (holding all else constant)[6] in order to contrast more fairly the historical record with the IPCC models' implied climate sensitivities. I perform these calculations next.

The IPCC *AR4* gives a best guess of +1.6 Watts per square meter (Wm^{-2}) as the total radiative forcing from all changes, both anthropogenic and natural (solar activity and aerosols from volcanic eruptions), occurring from preindustrial times through the year 2005 (Forster et al., 205). Again, this estimated total forcing went hand in hand with an observed temperature increase of 0.7°C. A hypothetical doubling of CO_2, holding all other forcing mechanisms constant at preindustrial values, would yield a forcing of +3.7 Wm^{-2} (Forster et al. 2007, 140). Unlike the case of CO_2 concentrations, radiative forcings are assumed to have a linear relationship with global temperature increases (Forster et al. 2007, 197). Therefore, the observed temperature increase and calculated total radiative forcing, from preindustrial time through 2005, yield an observed climate sensitivity of 1.6°C thus far, a little more than half of the official best guess of 3.0°C (the value Nordhaus uses in DICE 2007).

My 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 twentieth century (Hegerl 2007, 684). Rather than claiming falsification, I am 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 3.0°C warming from a doubling of CO_2 concentrations relies on feedback effects that, according to the IPCC models, have not yet fully manifested themselves or were

5. *Radiative forcing* is formally defined as "the change in net (down minus up) irradiance (solar plus longwave; in Watts per square meter, Wm^{-2}) at the tropopause [the boundary between the troposphere, where most weather occurs, and the stratosphere, the next atmospheric layer above the troposphere] after allowing for stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values" (Forster et al. 2007, 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 a change in the GHG concentration or volcanic eruptions. The higher the forcing, the more energy is retained within the system, which leads to increased temperatures.

6. 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* (Forster et al. 2007, 197). Yet even the IPCC does not weight mechanisms by their efficacies in its measure of cumulative forcing. This practice is due in part to the uncertainties involved and also to the fact that the best estimates show other mechanisms to have efficacies comparable (generally within 25 percent lower or higher) to that of CO_2.

offset by other factors through the year 2005. Therefore, future climatologists may substantially revise their estimate of climate sensitivity because presumed feedbacks and offsetting factors are not currently being modeled correctly.[7]

The point I wish to drive home to economists is that the IPCC estimate of climate sensitivity is *not* akin to measuring the price elasticity of the demand for potatoes. Rather, it is more analogous to predicting the effect of a sudden doubling of the money supply on long-run real gross domestic product (GDP). *This* type of task would yield a range of estimates from different economists, depending on the modeling approach each used, and the results would be much more susceptible to future revision compared to a task requiring merely a straightforward analysis of historical observations.

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

We come to the last major step in Nordhaus's 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 also rests on a surprisingly fragile foundation.

Nordhaus's basic approach is to estimate the damages in major sectors (such as agriculture, coastal regions, and so forth) 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.

Table 1 reproduces Nordhaus and Boyer's table 4.11 (2000, 97), in which they compare their own damage estimates of costs in billions of dollars for the United States[8] (for a warming of 2.5°C) with the estimates given in other studies. Note that negative numbers imply benefits.

If one does not delve into the specifics of each study, it would appear that Nordhaus and Boyer's damage estimates are quite reasonable because they generally fall within the range of other reputable studies. However, as mentioned earlier, we

7. For example, Petr Chylek and Ulrike Lohmann (2008) point to a climate sensitivity on the low end of the *AR4* range. Roy Spencer and his colleagues' (2007) study of intraseasonal variations in tropical systems is even more radical. Their analysis suggests that increasing temperatures may lead to fewer ice clouds, allowing more longwave radiation to leave the atmosphere and thus providing a potential negative feedback ignored by current climate models.

8. Of course, the ultimate issue is how much damage will be inflicted on the entire globe, not just on the United States alone, but the best studies, especially at the time of Nordhaus and Boyer 2000, focus on the United States. Moreover, Robert Mendelsohn reports (in response to my e-mail inquiry) that his current work for the globe is thus far consistent with net damages not occurring until temperature rises by more than 2.0 to 2.5°C.

Table 1
Comparison of Recent Impact Studies for 2.5°C Warming in the United States (in Billions of 1990 U.S.$)

	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
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

Source: Nordhaus and Boyer 2000, 97.

have good reason to prefer Robert Mendelsohn and James Neumann's findings over the others because these authors correct some of the biases of earlier studies. In a short pamphlet, Mendelsohn explains some of the flaws in 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. (1999, 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 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. (10–11)

> [New agroeconomic 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. (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. (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. (21–22)

Most readers of these passages will presumably agree that Mendelsohn's favored studies (in particular, those that he and coauthor Neumann commissioned for their 1999 collection) are more trustworthy than some of the more pessimistic ones in their respective sectors. Consequently, Nordhaus's damage estimates, generally falling in the middle of these disparate studies, may be too high.[9]

In any event, the most serious difficulty with Nordhaus's damage estimates is how strongly they rely on the impacts of so-called catastrophic outcomes, defined as an indefinitely long loss of at least 25 percent of global GDP. In other words, in

9. Unlike the damage function in DICE 1999, the damage function in DICE 2007 shows that *any* temperature increase, no matter how small, leads to net economic damages. This effect implies either that Earth is currently at its optimum temperature or that a global cooling would yield net benefits.

addition to the specific and carefully studied impacts of global warming on agriculture, recreation, and so forth, Nordhaus also wants to deal with the possibility that, say, the thermohaline circulation (the circulation of heat and salt among the world's oceans) will completely shut down. Yet, rather than explicitly modeling various catastrophic scenarios and assessing their impact (as well as their likelihood), Nordhaus and Boyer instead rely on a survey of experts, as explained 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 [Organization of Economic Cooperation and Development] Europe.
>
> To judge the importance of catastrophic impacts of climate change, a survey of experts pose [*sic*] 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?"[10]
>
> 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 scenario B. The assessment of the catastrophic scenarios varied greatly across respondents and particularly across disciplines. (2000, 87)

After describing their survey and the mean (median) probabilities for catastrophic loss under the three warming scenarios, Nordhaus and Boyer 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" (2000, 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" (88).

10. Here the authors insert a footnote, citing Nordhaus 1994b as the source of the survey text.

At this point, Nordhaus and Boyer wish to alter the estimates provided by the respondents to the original 1994 survey (given in the preceding block quotation). Yet instead of polling the experts again and calculating the new set of mean and median probabilities for the various warming scenarios, they simply adjust the original numbers in the following manner: "To reflect these growing concerns, *we assume [that] 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" (2000, 88, emphasis added). These are bold changes. To restate the issue: Nordhaus in 1994 asked experts to estimate (among other things) the probability of global GDP loss of 25 percent in the event of 3.0°C warming (Nordhaus 1994a). The surveyed experts gave him their answers, from which he computed the mean. By 1999, further research had made these scenarios seem more plausible or catastrophic. So Nordhaus and Boyer took the original average of probabilities reported by the experts, *doubled it*, and then assigned this new figure 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 3.0°C* mentioned in the original survey.[11] More recent research suggests that at least some of these catastrophic scenarios were false alarms.[12]

I have devoted so much space to documenting the source of these estimates because, at least in the 1999 version of Nordhaus's model, they constitute the *majority* of the damages from climate change. Table 2 reproduces portions of table 4.10 from Nordhaus and Boyer 2000 that summarize the sectoral impacts of a 2.5°C warming.

As table 2 indicates, the global damages (weighted by the output in each region) from a 2.5°C warming are estimated at 1.50 percent of GDP, yet 1.02 percent of this GDP loss (that is, 68 percent of the total damages) is attributable to the "catastrophic impact" scenarios described earlier.[13] Inasmuch as this particular sectoral impact was

11. In fairness to Nordhaus and Boyer, convenience apparently guided some of these choices. For example, at the time their book was published (2000), the scientific consensus was that a benchmark doubling would lead to a 2.5°C warming, which presumably explains why they adjusted the temperature threshold down from 3.0°C, as the original survey had indicated.

12. According to the 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" (Meehl et al. 2007, 818). A 2006 *Science* article was entitled "Global Climate Change—False Alarm: Atlantic Conveyor Belt Hasn't Slowed Down after All" (Kerr 2006), as explained in Lomborg 2007.

13. 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, I have omitted this subtlety because Nordhaus 2008 drops the "willingness to pay" approach to damage estimates and deals with risk aversion directly.

Table 2
Summary of Sectoral Impacts in Nordhaus's 1999 Approach (in Percentage of GDP)

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

Source: Parts of table 4.10 in Nordhaus and Boyer 2000, 91.

not derived in a rigorous way, it may vastly overestimate 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, I can modify the latest version of Nordhaus's DICE model and observe the effect on its recommended carbon tax profile. In particular, I can run Nordhaus's 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)[14] and altering the estimate of climate sensitivity from 3.0°C down to 2.5°C.[15] These two changes drastically affect the "optimal" carbon tax for a given year.

As table 3 indicates, the uncertainties discussed in this section drastically affect the magnitude of the economically efficient Pigovian tax on carbon. The proponent

14. Of course, the complete removal of catastrophic impacts is unjustified. I do so merely to show how much of Nordhaus's optimal tax is due to this sector (as well as to a climate sensitivity of 3.0°C rather than 2.5°C).

15. For those familiar with the model, I reduced T2XCO2 from 3.0 to 2.5 and reduced A2 from 0.0028388 to 0.000768.

Table 3
DICE Model Optimal Carbon Tax Original versus Adjusted Values (2005 U.S.$ per Ton of Carbon)

	2015	2025	2035	2045	2055	2065	2075
Nordhaus 2008	$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

Source: Nordhaus 2008, 92, and author's simulations of DICE runs.

of strict measures can naturally argue that Nordhaus may be *underestimating* the risks of inaction. Although that claim may be true, I believe the balance of evidence lies in the favor of conservatism because I 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.

Idealized Government Solutions versus Practical Market Solutions

Thus far, I have focused on technical criticisms of Nordhaus's 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's proposal and others like it are overly optimistic about the potency of government regulation and unduly pessimistic about a market economy's creative responses. Those who are 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

The 2007 DICE model contains simulations not just of the baseline (no controls) and the optimal carbon tax scenarios, but of many other policies as well. These calculations show that the dangers of an overly ambitious or inefficiently structured policy can swamp the potential benefits of a perfectly calibrated and efficiently targeted one (that is, the optimal carbon tax scenario). As table 4 indicates, Nordhaus's optimal plan yields net benefits of approximately $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 that Gore's plan would make the world more than $21 trillion poorer than it would be if there were no controls on carbon.

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

Table 4
DICE's Relative Benefits of Different Climate Policies (in Trillions of 2005 U.S.$)

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 the United States	+0.63	21.38	0.58	21.96
Kyoto without the United States	+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 percent emissions cut	−21.36	10.05	33.90	43.96

Note: PDV = present discounted value.
Source: Adapted from Nordhaus 2008, 89.

costs against marginal benefits from avoided climatic damage; 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 proposed instead to limit CO_2 concentrations to one and a half times their preindustrial value (that is, 420 ppm), then both abatement costs *and* environmental damages would be lower than the amounts his actual plan 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 that cannot vary over time (unlike the carbon tax) will be worse the farther 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 with the policy of limiting temperature increases to 1.5°C. As table 4 indicates, both policies have roughly the same benefits in terms of reduced environmental damage, but the former policy entails $160 billion in additional 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 explains, this paradoxical outcome occurs because CO_2 concentrations in the temperature-targeting 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).

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* it 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 take the form of imposing such a cap. Not only do they fail to match increments in avoided climate change with the corresponding opportunity costs in terms of forgone production, but they 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 staggeringly costly proposals laid out in table 4 are not interesting thought experiments invented by Nordhaus. On the contrary, they are inspired by actual proposals that policymakers are discussing seriously, including the proposals by Stern (2007) and Gore, with their *net* costs of more than $14 and $21 trillion, respectively.

Table 5
Arbitrary Climate Goals Impose Unnecessary Abatement Costs

Strategy and Variable	2005	2015	2025	2050	2100	2200
Limit to 420 ppm						
CO_2 conc. (ppm)	379.80	405.20	415.10	420.20	420.20	420.20
Temp. increase (°C)	0.73	0.94	1.10	1.36	1.61	1.78
Limit to 1.5° C						
CO_2 conc. (ppm)	379.80	405.20	418.20	434.40	400.40	388.20
Temp. increase (°C)	0.73	0.94	1.12	1.43	1.50	1.50

Source: Adapted from tables 5-7 and 5-8 of Nordhaus 2008, 103 and 106.

Policies Will Not Be Implemented in Textbook Fashion

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, a cap-and-trade scheme, or some other regime of controls and regulations, some governments will not strictly enforce its provisions. Although we all are living on one planet, different regions will be affected in different ways by climate change and by efforts to limit carbon emissions. For example, Russia has much less to lose from global warming than Egypt, and a return to 1990 emissions levels would imply a much greater 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) participate nominally while exempting favored sectors. In order to achieve the estimated benefits in table 4, the "good" proposals must be enforced not only on a worldwide scale, but also nonstop for centuries. If a severe recession occurs 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 might be forfeited.

Nordhaus himself considers 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. (2008, 19)

Before leaving this point, I should clarify Nordhaus's 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 conclusion 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 naive with regard 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" (2008, 68).

Unfortunately, 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 nonparticipation—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 the purposes of getting revenue or doing favors for domestic industries?

In this context, then, we must ask economists to look before they leap into supporting a massive new global carbon tax (or any other such scheme). Such a tax might very well lead to the worst of both worlds, with global production heavily distorted because of 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 reliance on economic growth (Clark and Lee 2004) is not a politically popular approach, it is a robust means of dealing with climate change. 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, and so forth). Government programs to avert global warming will undeniably stifle economic growth, thereby ironically limiting people's ability to adapt in such ways.[16]

16. Robert Bradley suggests a "no regrets" approach, where policy changes are made that both reduce GHG emissions and promote economic efficiency (2003, 119–21). Such changes include congestion pricing for roads and the elimination of subsidies for energy use.

To be sure, in any formal model with a negative externality caused by carbon emissions, the decentralized market outcome will be Pareto inefficient. However, such models, by their very nature, cannot incorporate the superior information that future generations will possess. By bequeathing to these generations a freer economy and more material wealth, we give them flexibility to deal with environmental challenges as they occur. Yes, in principle, Nordhaus's optimal carbon tax might be repealed in 2068 if a bioengineering solution presents itself or if a commercially viable nonfossil fuel is developed, and proponents of a carbon tax argue that uncertainty about the future should not prevent us from always adopting what appears to be the best option at present. In practice, however, this argument is dangerous because massive new government programs will be extremely difficult to unwind as new information becomes available.

Conclusion

Many economists favor some form of government penalty on CO_2 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. Besides the theoretical difficulties, we cannot dismiss the likelihood that politicians will rely on politics—rather than pure science—to implement the recommended programs. Rather than depending 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 at each major step of the case for reliance on a carbon tax, economists should reconsider their current support for such a policy.

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