CLIMATE

To Hedge or Not Against an Uncertain Climate Future?

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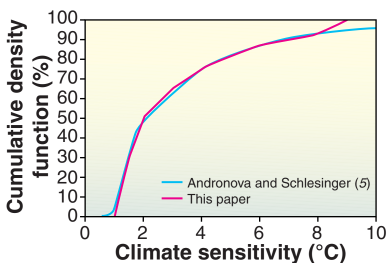
It has been over a decade since Nordhaus (*1*) published his seminal paper on mitigation policy for climate change. His question was "To slow or not to slow?"; his answer was derived from a traditional cost-benefit approach. He found that a tax levied on fossil fuel in proportion to its carbon content, which would climb over time at roughly the rate of interest, maximized global welfare. Although many more analyses of the same question have since been published, his results are still robust if one assumes a deterministic world in which decision-makers are prescient. However, no decision-maker has perfect foresight, and the uncertainty that clouds our view of the future has led some to argue that near-term mitigation of greenhouse gas emissions would be foolish. Such policy would impose immediate costs, they argue, and have uncertain long-term benefits.

We take a different approach in this Policy Forum by assuming that decision-makers will someday become so concerned about the potential damages associated with climate change that they will take action. Even though it is impossible to determine exactly what sort of mitigation target these future policies might ultimately adopt, a "wait-and-see" approach may no longer be the best near-term policy choice. Should we move soon to intervene in global energy markets as a hedge against the expected cost of meeting a currently unknown policy target?

We follow the modeling approach adopted in the hedging experiments conducted by Manne (*2*) and Yohe (*3*) for the Energy Modeling Forum to explore the policy implications of extreme events. Our analysis is based on a modified version of DICE-99 (Dynamic Integrated Model of Climate and the Economy)—a widely respected model of global economic activity and the damages associated with greenhouse gas–induced temperature change (*4*). We assume that decision-makers evaluate the economic merits of implementing near-term global mitigation policies starting in 2005 that will be in force for 30 years. They know that they will be able to "correct" their policy in 2035, and we assume that decisions will be informed by perfect information about both the climate sensitivity and the policy target. Their goal will be to maximize the expected discounted value of gross world product (GWP, the global equivalent of gross domestic product) across the range of options that will be available at that time (see online material for details and definitions).

The uncertainty in our understanding of the climate system against which these policies will be framed is portrayed in the figure (below). It shows a continuous cumulative distribution function (CDF) of climate sensitivity estimated by Andronova and Schlesinger (*5*) (where climate sensitivity is the temperature increase that results from a doubling of atmospheric concentration of greenhouse gases relative to preindustrial levels). It also shows a version of the same CDF that allowed us, for reasons of practicality, to work with a limited number of sensitivities that were nonetheless representative of the continuous CDF. Each sensitivity is associated with a probability, so that it conformed with the continuous version. Both representations show that climate sensitivities as high as 9°C are possible.



Cumulative distributions of climate sensitivity (*5*).

Several structural and calibration modifications of the DICE-99 model were required to accommodate the wide range displayed in the figure. Because responding to high sensitivities could be expected to put enormous pressure on the consumption of fossil fuel, for example, we limited the rate at which the global economy could "decarbonize" itself (i.e., reduce the ratio of carbon emissions to global economic output) to 1.5% per year.

Calibrating the DICE-99 model to alternative climate sensitivities that span the range displayed in the figure was more involved, because the DICE model includes a parameter that reflects the inverse thermal capacity of the atmospheric layer and the upper oceans. Larger climate sensitivities were associated with smaller inverse capacity values, so that the model could match observed temperature data when run in the historical past. The parameter was defined from optimization of the global temperature departures calculated by DICE and calibrated against the observed departures from Jones and Moberg (*6*) for the prescribed range of the climate sensitivities from 1.5° to 9°C (*7*).

Modest near-term mitigation would maximize discounted GWP, even if no mitigation was done after 2035 (see the supporting online text). Achieving optimality or even meeting specific concentration targets would not, however, necessarily hold temperatures below the 2° to 3° range identified by Smith and Hitz (*8*) and the Intergovernmental Panel on Climate Change (IPCC) (9), as a threshold above which damages caused by gradual climate change would climb dramatically, and by Schneider (*10*) and the IPCC (*9*), as a threshold above which abrupt changes become much more likely. We therefore focused our attention on mitigation pathways designed to limit temperature increases to four targeted levels (recorded in the first row of the table, next page) that straddle this critical threshold.

We assumed that global policy-makers would choose among these options in 2035, when the true climate sensitivity would be revealed; but each target was assumed to be equally likely for the purposes of setting near-term policy in 2005. Maximum discounted GWP was computed using the modified DICE-99 framework for initial 2005 taxes ranging from $0 to $50 per ton of carbon. Some combinations involved doing too little in the near term, so GWP fell as downstream mitigation "ramped-up" to achieve the prescribed temperature limit. Other combinations involved doing too much in the near term, so GWP again fell even though mitigation could be "turned down" after 2035. An ini-

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tial tax of roughly $10 per ton of carbon (about 5¢ for a gallon of gasoline that would grow at the rate of interest over time) balances these two sources of loss to maximize expected GWP.

Comparisons drawn from the DICE model across the requisite adjustments for the $10 initial tax and for a wait-and-see policy in a "robustness" chart are displayed in the table (*11*). The second column shows that a 2° target could not be achieved, even if mitigation policy began in 2005, for climate sensitivities above 3°; they are "impossible now" in the parlance of the table. Second, 2° and 2.5° targets could not be achieved if an initial $10 tax policy were imposed in 2005 for climate sensitivities above 4° and 6°, respectively ("impossible later" in the table). Doing nothing through 2035 would put 3° beyond the range of possibility if the climate sensitivity were 7° or higher.

DISCOUNTED ADJUSTMENT COSTS ($) GIVEN AN INITIAL TAX OF $10

Climate sensitivity (degrees)	Temperature target (degrees) 2	2.5	3	3.5
1.5	$0	$0	$0	$0
2	$2	$1	$0	$0
3	$4	$3	$1	$0
4	IL	$6	$2	$0
5	IL	$12	$3	$0
6	IN	IL	$4	$1
7	IN	IL	$6	$3
8	IN	IL	$9	$5
9	IN	IL	$12	$9

DISCOUNTED ADJUSTMENT COSTS ($) GIVEN NO MITIGATION THROUGH 2035

Climate sensitivity (degrees)	Temperature target (degrees) 2	2.5	3	3.5
1.5	$32	$11	$3	$0
2	$38	$22	$16	$4
3	$180	$29	$18	$22
4	IL	$60	$24	$24
5	IL	$142	$25	$25
6	IN	IL	$27	$28
7	IN	IL	IL	$34
8	IN	IL	IL	$35
9	IN	IL	IL	$38

Implementing near-term mitigation policy versus no mitigation of carbon. Comparing the robustness of implementing near-term mitigation policy through 2035 beginning with an initial tax of $10 per ton of carbon (rising to nearly $33 per ton in 2035) with the robustness of imposing no mitigation policy through 2035. Values report losses in discounted GWP (in billions of dollars) when the indicated near-term policy is compared with the minimum-cost deterministic path. Annual losses (and gains) are discounted back to 2005 (see the supporting material on *Science* online). "IN" means "impossible now"; i.e., that the indicated temperature target cannot be reached by any mitigation policy initiated in 2005. "IL" means "impossible later"; i.e., that the indicated targets could not be achieved by any adjustments in 2035 to the specified near-term interventions in 2005.

An initial $10 tax policy is remarkably robust across the remaining possibilities, as shown in the table. Discounted adjustment costs are smaller than $10 billion except for high climate sensitivities near the border of the impossibility frontier. A wait-and-see approach leaves the global economy open for far more serious adjustment costs. Except for higher targets with low sensitivities, doing nothing through 2035 imposes costs in excess of $20 billion in more than half of the possible cases and significantly larger than $50 billion for low temperature targets even with lower climate sensitivities (*12*). These costs are comparable, for example, to the estimated cost of rebuilding Iraq.

We need to be clear that the initial tax would climb over time, as in the original Nordhaus paper (*1*), at the rate of interest. Although some energy sectors around the world might not respond significantly to the initial $10 intervention, the model also captures more vigorous responses in subsequent years—the results of additional incentives created by persistent and growing carbon taxes designed to punish those who ignore conservation and substitution opportunities.

It should not be a surprise that hedging is a preferred strategy in a world where a temperature target may be selected sometime in the future. People buy insurance against extreme events when the risks affect private property, and societies require insurance when potential losses are distributed across a population. It is, however, surprising that climate insurance over the near term can be so inexpensive and that an economically efficient near-term hedging policy can be so robust across a wide range of futures in comparison with doing nothing. The point is that paralysis in near-term action can make temperature targets as low as 3° impossible to achieve if the climate sensitivity turns out to be higher than 6°. Moreover, the cost of adjustment measured in terms of discounted GWP can be many times higher for lower climate sensitivities if nothing were done for 30 years. In short, taking an insurance approach to the near-term mitigation question strongly supports starting modest but persistent intervention on a global scale as soon as possible.

The specific cost estimates are, of course, highly dependent on the global modeling context of the DICE-99 model, the analytical decision to include only uncertainty about climate sensitivity in the analysis, and the identified boundaries of the "impossibility frontier"; i.e., the temperature limits that could not be achieved now and others that could not be achieved if mitigation were delayed for 30 years. In addition, it is highly unlikely that many (if any) of the fundamental uncertainties associated with the climate problem will be resolved over the next 30 years. As a result, we should expect that "midcourse" corrections will involve repeated hedging exercises and thus, relative to the modeling framework presented here, more uncertainty. The qualitative conclusion supporting modest near-term mitigation is, nonetheless, extremely robust, because it is uncertainty that produces its value. Adding other sources of uncertainty would simply add to that value by widening the range of futures over which we must hedge. Uncertainty is the reason for acting in the near term, and that uncertainty cannot be used as a justification for doing nothing.

References and Notes

1. W. D. Nordhaus, *Econ. J.* **101**, 920 (1991).
2. A. S. Manne, "A summary of poll results: EMF 14 Subgroup on Uncertainty" (Stanford Univ., Stanford, CA, 1995).
3. G. Yohe, *Glob. Environ. Change* **6**, 87 (1996).
4. W. D. Nordhaus, J. Boyer, *Warming the World: Economic Models of Global Warming* (MIT Press, Cambridge, MA, 2001).
5. N. G. Andronova, M. E. Schlesinger, *J. Geophys. Res.* **106** (D19), 22605 (2001).
6. P. D. Jones, A. Moberg, *J. Climate* **16**, 206 (2003).
7. Table S1 of the supporting material provides the precise calibration of the CDF for climate sensitivity.
8. J. Smith, S. Hitz, "Estimating the global impact of climate change" [ENV/EPOC/GSP(2003)12, Organization for Economic Co-operation and Development (OECD), Paris, 2003].
9. Intergovernmental Panel on Climate Change (IPCC), *Climate Change 2001: Impacts, Adaptation and Vulnerability* (Cambridge Univ. Press, Cambridge, 2001), chapter 19.
10. S. Schneider, "Abrupt non-linear climate change, irreversibility and surprise" (ENV/EPOC/GSP(2003)13, OECD, Paris, 2003).
11. R. J. Lempert, M. E. Schlesinger, *Clim. Change* **45**, 387 (2000).
12. These costs represent only the added expense of having been wrong in setting mitigation policy relative to the ultimate resolution of the temperature target and of uncertainty about climate sensitivity. The supporting online material records net benefits (using perfect knowledge in 2005 as a baseline) to show that the discounted costs of achieving specific temperature targets can be much larger than these adjustment costs.

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Supporting Online Material
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