# Economic aspects of global warming in a post-Copenhagen environment

**William D. Nordhaus**[1]

Department of Economics, Yale University, New Haven, CT 06520

Contributed by William D. Nordhaus, May 10, 2010 (sent for review February 4, 2010)

**The science of global warming has reached a consensus on the high likelihood of substantial warming over the coming century. Nations have taken only limited steps to reduce greenhouse gas emissions since the first agreement in Kyoto in 1997, and little progress was made at the Copenhagen meeting in December 2009. The present study examines alternative outcomes for emissions, climate change, and damages under different policy scenarios. It uses an updated version of the regional integrated model of climate and the economy (RICE model). Recent projections suggest that substantial future warming will occur if no abatement policies are implemented. The model also calculates the path of carbon prices necessary to keep the increase in global mean temperature to 2 °C or less in an efficient manner. The carbon price for 2010 associated with that goal is estimated to be $59 per ton (at 2005 prices), compared with an effective global average price today of around $5 per ton. However, it is unlikely that the Copenhagen temperature goal will be attained even if countries meet their ambitious stated objectives under the Copenhagen Accord.**

abatement strategies | climate change | Copenhagen Accord | economic growth | integrated assessment models

The world is far along in what Roger Revelle and Hans Suess called "our great geophysical experiment" (1). The failure of nations in Copenhagen in December 2009 to reach a concrete agreement to extend and broaden the Kyoto Protocol raises the prospect that attempts to limit atmospheric concentrations of carbon dioxide ($CO_2$) and other greenhouse gases (GHGs), with the resulting global temperature increases, may prove politically difficult. This study reports improved estimates of the likely trajectories of global output, GHG emissions, climate change, and damages in the coming decades.

Climatologists and other scientists have warned for more than half a century that the accumulation of $CO_2$ and other GHGs in the atmosphere is leading to global warming and other significant climatic, ecological, and societal changes. However, the economic, political, and institutional issues involved in limiting GHG emissions have only begun to be considered over the past 2 decades. The difficulty is that reducing emissions is an extreme "global public good," meaning that no single nation can capture for itself a substantial part of the benefits from its own emission reductions (2). The intellectual challenge is daunting, raising formidable issues of data, modeling, uncertainty, international coordination, and institutional design. In addition, the economic stakes in climate-change policy are huge.

What are the stakes if nations fail to reach meaningful climate-change agreements? In other words, what are the climatic and economic consequences of uncontrolled emissions of GHGs over the coming decades? These questions become particularly salient, given the apparent difficulties of reaching a binding and effective international agreement. Surprisingly, the impressive work of scientific bodies such as the Intergovernmental Panel on Climate Change (IPCC) does not address the likely trajectory of uncontrolled emissions, either in the past two rounds of assessments or prospectively in the coming fifth round. The present study attempts to explain the issues and provide some tentative answers.

## The Copenhagen Accord

The agreed framework for all international climate-change deliberations is the United Nations Framework Convention on Climate Change, ratified in 1994. That document stated, "The ultimate objective…is to achieve…stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (3). The Framework Convention was implemented in the Kyoto Protocol in 1997, in which both high-income countries and countries in transition from socialism agreed to binding emissions limits for the 2008–2012 period. However, the reality of global warming policy has lagged far behind scientific prescriptions. This is seen in the attrition in covered emissions. The original Kyoto Protocol covered ≈66% of 1990 industrial $CO_2$ emissions. However, with the failure of the United States to ratify the agreement and the decline in the relative emissions of rich countries, the Kyoto Protocol currently covers only ≈27% of global emissions.

The 2009 Copenhagen meeting was designed to negotiate a successor agreement for the post-Kyoto period. Because of deep divisions about costs and the distribution of emissions reductions, the meeting concluded without a binding agreement. However, it did lead to an agreement known as the "Copenhagen Accord" (4). The accord adopts a target of limiting the increase in global mean temperature, "recognizing the scientific view that the increase…should be below 2 degrees Celsius." Those looking for a silver lining behind the cloudy outcome have pointed to the fact that developing countries joined the accord. A close look reveals, however, that developing countries committed themselves to very little. They agreed to "communicate" their "nationally appropriate mitigation actions seeking international support efforts," but no binding targets for developing countries were set. By mid-2010, most countries have communicated their plans.

The reality behind the accord is not encouraging. To begin with, even if the high-income countries fulfilled their commitments, these would probably not achieve anything close to the 2 °C target, as is shown below. Meanwhile, progress on reaching a more binding agreement has been glacial at best. At present, a global agreement is waiting for the United States to take credible legislated steps. Continued delay in adoption of climate-change policies by the United States may lead to a domino effect in which other countries follow the US inaction.

Given these developments, it is useful to review the prospects for climate change and the economic implications, both for the case in which controls are implemented as envisioned by the Copenhagen Accord and for the case in which the present stalemate continues. This report presents the results of an updated version of the regional integrated model of climate and the economy (RICE model), denoted the RICE-2010 model. The model is a regionalized, dynamic, integrated assessment model of

Author contributions: W.D.N. designed research, performed research, analyzed data, and wrote the paper.

The author declares no conflict of interest.

Freely available online through the PNAS open access option.

[1]E-mail: william.nordhaus@yale.edu.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1005985107/-/DCSupplemental.

the global economy and climate change that incorporates an end-to-end treatment of economic growth, emissions, the carbon cycle, climate change, damages, and emissions controls. The model allows the computation of internally consistent projections of the effects of alternative policy regimes. I begin with a succinct description of the model.*

## The RICE-2010 Model

The RICE model views climate change in the framework of economic growth theory. In a standard neoclassical optimal growth model known as the Ramsey model, society invests in capital goods, thereby reducing consumption today so as to increase consumption in the future (5, 6). The RICE model modifies the Ramsey model to include climate investments. The capital stock of the conventional model is extended to include investments in the environment ("natural capital"). Emissions reductions in the extended model are analogous to capital investments in the mainstream model. That is, we can view concentrations of GHGs as "negative natural capital" and emissions reductions as lowering the quantity of that negative capital. Emissions reductions lower consumption today but, by preventing economically harmful climate change, increase consumption possibilities in the future.

The model divides the world into 12 regions. Some are large countries such as the United States or China; others are large multicountry regions such as the European Union or Latin America. Each region is assumed to have a well-defined set of preferences, represented by a social welfare function, and to optimize its consumption, GHG policies, and investment over time. The social welfare function is increasing in the per capita consumption of each generation, with diminishing marginal utility of consumption. The importance of a generation's per capita consumption depends on its relative size. The relative importance of different generations is measured using a pure rate of time preference, and the curvature of the utility function is given by the elasticity of the marginal utility of consumption. These parameters are calibrated to ensure that the real interest rate in the model is close to the average real interest rate and the average real return on capital in real-world markets (7, 8).

The model contains both a traditional economic sector like that found in many economic models and geophysical relationships designed for climate-change modeling.

**Economic Sectors.** Each region is assumed to produce a single commodity, which can be used for consumption, investment, or emissions reductions. Each region is endowed with an initial stock of capital and labor and with an initial and region-specific level of technology. Population data are from the United Nations, updated with more recent estimates through 2009, with projections using the United Nations' estimates to 2300 (9). Output is measured as standard gross domestic product (GDP) in constant prices, and the GDPs of different countries are converted into 2005 US international prices using purchasing-power-parity exchange rates. Output data through 2009 are from the World Bank and the International Monetary Fund (IMF), with projections to 2014 from the IMF (10, 11). $CO_2$ emissions data are from the US Energy Information Administration and Carbon Dioxide Information Analysis Center and are available through 2008.

Population growth and technological change are exogenous in the baseline model, whereas capital accumulation is determined by optimizing the flow of consumption over time. Output is determined using a Cobb–Douglas production function with capital, labor, and carbon-energy as inputs. Technological change takes two forms: economy-wide technological change and carbon-energy-saving technological change. The former is Hicks-neutral, and the latter is modeled as reducing the ratio of $CO_2$ emissions to carbon-energy inputs. Technological change is projected for a frontier region (the United States), and other countries are assumed to converge partway to the frontier. For convenience, both carbon-energy inputs and industrial emissions are measured in units of carbon weight (7, 12). Economic growth rates for the different regions are provided in *SI Appendix*, Table S1.

I calibrate the energy-related parameters using data on historical GDP and $CO_2$ emissions for the period 1960–2008. The model uses a cost function for $CO_2$ emissions reductions that is drawn from more detailed models at the national and regional levels from the IPCC Fourth Assessment Report (13) and the Energy Modeling Forum 22 report (14). *SI Appendix*, Fig. S1 shows historical rates of decarbonization. Additionally, there is a backstop technology that can replace all carbon fuels at a relatively high price ($1,260 per ton of carbon for the emissions-weighted global average), declining over time, drawn from IPCC surveys and other sources (15). It is assumed that the backstop technology becomes increasingly competitive with carbon fuels after 2250, such that emissions decline rapidly thereafter. The supply curve allows for limited, albeit very large, long-run supplies of carbon fuels. In the optimal-growth framework, energy resources are efficiently allocated across time, which implies that low-cost carbon resources have scarcity prices (called "Hotelling rents") and that carbon-energy prices rise over time (16).

Solution of a multicountry general economic equilibrium model poses major modeling issues. I have used a modification of the Negishi procedure introduced by Nordhaus and Yang (17). The modification is that the welfare weights are set to equalize the period-by-period marginal utilities using the weighted average marginal utility, where each region's weights are the regions' shares of the global capital stock in a given period.

**Geophysical Sectors.** The geophysical part of the model contains a number of relationships that link together the different factors affecting climate change. These include simplified relationships to capture $CO_2$ emissions, a carbon cycle, radiative forcings, a simple climate model, and regional climate-damage relationships. Each of these is drawn from more complex models and can be regarded as models of very simplified structure.

Emissions include all GHG emissions, although they comprise primarily $CO_2$ emissions. Endogenous emissions in the RICE-2010 model are limited to industrial $CO_2$. Chlorofluorocarbons are now outside the climate-change protocols. Other contributions to global warming are taken as exogenous. These include $CO_2$ emissions from land-use changes, non-$CO_2$ GHGs, and sulfate aerosols (18, 19).

The model uses a three-reservoir model calibrated to existing carbon-cycle models to calculate the carbon cycle. Climate change is represented by global mean surface temperature, and the relationship uses the results of the Fourth Assessment Report of the IPCC to estimate the lag structure and the equilibrium, which are calibrated to include the decreasing uptake of carbon with rising temperature (19).The RICE-2010 model contains a module with calculations of sea-level rise (SLR) associated with different temperature trajectories. The current version assumes that the equilibrium temperature-sensitivity coefficient is 3.2 °C per $CO_2$ doubling. The model has also been checked by comparing results with those of the 2009 version of the Model for the Assessment of Greenhouse-Gas Induced Climate Change (MAGICC).

Understanding the market and nonmarket impacts of climate change continues to be the thorniest issue in climate-change economics. The RICE-2010 model provides a revised set of damage estimates based on a recent review of the literature (20, 21). Damages are a function of temperature, SLR, and $CO_2$ concentrations and are region-specific. To give an idea of the estimated

*The equations of the model, along with key assumptions, are available in *SI Appendix*. The model is also available as an Excel spreadsheet downloadable from the author's website (http://www.econ.yale.edu/~nordhaus/homepage/homepage.htm). The results reported here are based on the RICE model version of April 25, 2010.

damages in the uncontrolled (baseline) case, those damages in 2095 are $12 trillion, or 2.8% of global output, for a global temperature increase of 3.4 °C above 1900 levels.

There have been many recent studies concerned with abrupt and catastrophic climate change (22–24). Estimates for the economic costs of such scenarios are included in the damage estimates in the RICE model, but the model does not build in a precise tipping point at a given temperature increase, because such a tipping point has not been reliably determined.

## Policy Scenarios

I examine the economic and climate trajectories associated with five different international policy approaches:

(*i*) Baseline: No climate-change policies are adopted.

(*ii*) Optimal: Climate-change policies maximize economic welfare, with full participation by all nations starting in 2010 and without climatic constraints.

(*iii*) Temperature-limited: The optimal policies are undertaken subject to a further constraint that global temperature does exceed 2 °C above the 1900 average.

(*iv*) Copenhagen Accord: High-income countries implement deep emissions reductions similar to those included in the current US proposals, with developing countries following in the next 2 to 5 decades.

(*v*) Copenhagen Accord with only rich countries: High-income countries implement deep reductions as in scenario 4, but developing countries do not participate until the 22nd century.

The baseline can be interpreted as complete inaction and stalemate on climate policies. The "optimal" scenario assumes the most efficient climate-change policies; in this context, efficiency involves a balancing of the costs of abatement and the benefits of reduced climate damages. Although unrealistic, this scenario provides an efficiency benchmark against which other policies can be measured. The "temperature-limited" scenario is a variant of the optimal scenario that builds in a precautionary constraint that a specific temperature increase is not exceeded. The Copenhagen Accord scenario assumes that the announced emissions-reduction policies for high-income countries for the near term are implemented. It then extends these to other high-income countries to parallel the United States-proposed reductions. Developing countries are assumed to follow within a few decades. *SI Appendix*, Table S2 shows the base and commitment years for different regions. The fifth scenario is the same as the Copenhagen Accord scenario, but developing countries do not participate until well into the 22nd century. For this scenario, the high-income participants are the United States, the European Union, Japan, Russia, and a group of other high-income countries.

## Major Results

**The Major Cases.** The results presented here should be viewed as only suggestive and illustrative. They come from a single model and modeling perspective, and most of the relationships are subject to large uncertainties.

Figs. 1–4 report the main results. Further results are available in *SI Appendix*, Table S3. Fig. 1 shows global $CO_2$ emissions under each of the five policy scenarios. Unrestrained emissions are estimated to grow very rapidly. Emissions under the optimal and temperature-limited scenarios are essentially flat for the next 2 to 6 decades and then decline. The optimal path imposes a cut in global emissions of 50% from 2005 in 100 y, and the temperature-limited path prescribes zero emissions at about 2075.

Atmospheric concentrations of $CO_2$ rise sharply under the baseline path, reaching 793 ppm by 2100 (Fig. 2 and *SI Appendix*, Table S3 presents the numerical data). The optimal and temperature-limited paths show some slight continuation in the rise of concentrations from current levels, peaking between 500 and 600 ppm. (Note that these refer to $CO_2$ concentrations rather than to $CO_2$-equivalent concentrations.) Radiative forcings (not shown) peak at 4.4 $W/m^2$ in the optimal path and at 3.2 $W/m^2$ in the temperature-limited path. These forcings include those from other GHGs as well as estimates of other anthropogenic forcings, such as from sulfates.

Global temperature projections, shown in Fig. 3, rise sharply under the baseline, with increases of 3.5 °C in 2100 and 5.7 °C in 2200 and a peak (not shown) at 6.7 °C, all relative to 1900. The optimal and temperature-limited paths rise in the early 21st century because of the momentum of past emissions. They then bend downward as emissions are reduced, peaking at 2 °C (obviously) for the temperature-limited path and at 3.0 °C for the optimal path. Two important results are that the optimal path has a relatively low maximum temperature and the temperature increase for this path averaged over 2100–2300 is 2.7 °C.

Perhaps the most important outputs of integrated economic models of climate change are the near-term "carbon prices." This is a concept that measures the marginal costs of reductions of emissions of GHGs. In a market environment, such as a cap-and-trade regime, the carbon prices would be the trading price of

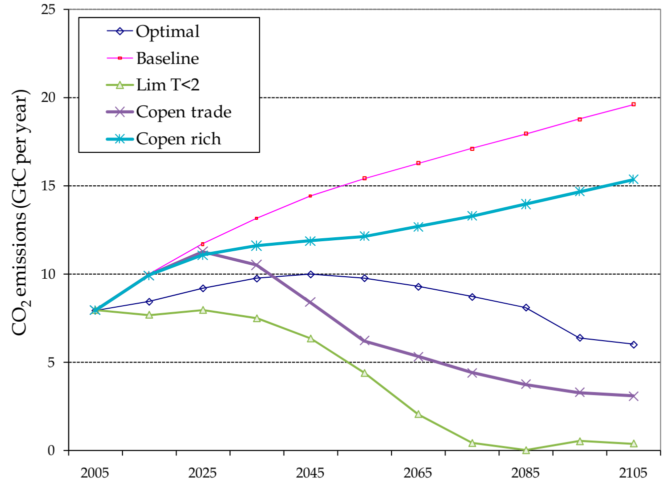


**Fig. 1.** Projected emissions of $CO_2$ under alternative policies. Copen, Copenhagen.

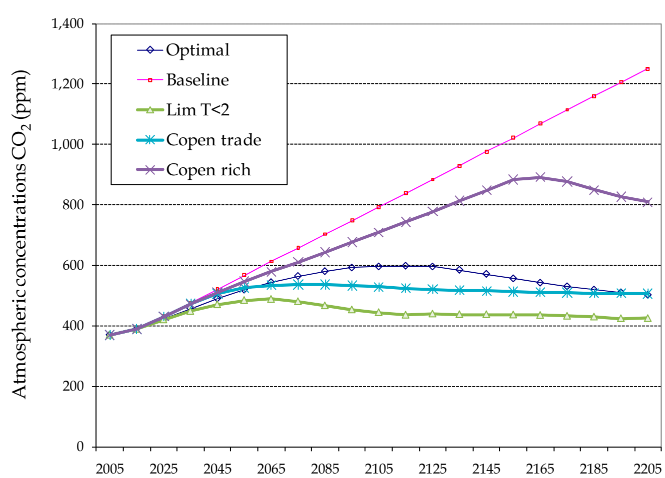


**Fig. 2.** Atmospheric concentrations of $CO_2$ under alternative policies. Copen, Copenhagen.

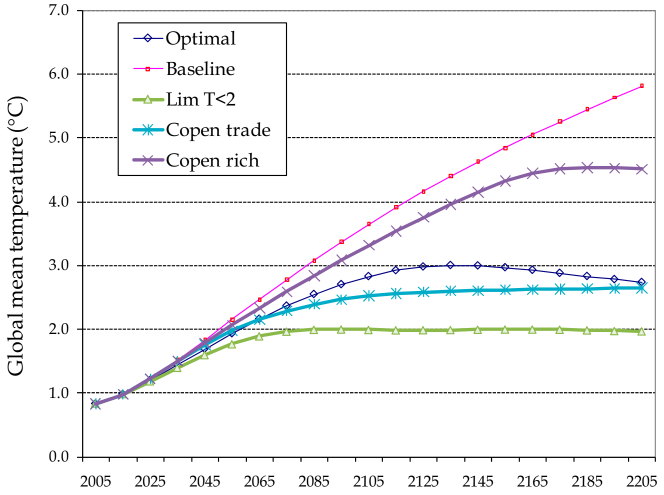


**Fig. 3.** Global temperature increase (°C from 1900) under alternative policies. Copen, Copenhagen.

carbon emission permits. We can also judge different policies against benchmarks by examining their near-term carbon prices, which are shown for the different scenarios in Table 1, in 2005 dollars. A graphical comparison is shown in *SI Appendix*, Fig. S2. Carbon prices, equal to the Hotelling rents on carbon fuels in the baseline scenario, are essentially zero and are therefore not depicted. Prices under the optimal and temperature-limited scenarios at first rise to \$38 and \$79 per ton, respectively, by 2015. Prices under the optimal scenario then continue to rise sharply until they reach the projected backstop price.

Global average carbon prices under the two Copenhagen Accord scenarios are much lower than under the previous scenarios for the first 2 decades of the projections, reflecting the gradual introduction of policy interventions as well as incomplete participation. Note that the effective carbon price today (around \$5 per ton) is well below that required under either the optimal or temperature-limited scenario. Numerical values for carbon prices for the different scenarios are reported in *SI Appendix*, Table S4, and those for the Copenhagen Accord with no trading are reported in *SI Appendix*, Table S5. *SI Appendix*, Tables S6 and S7 present the associated emissions control rates for the optimal case and the Copenhagen Accord with full trading.

Table 2 shows the large stakes involved in climate-change policies as measured by aggregate costs and benefits. Using the model discount rates, the optimal scenario raises the present value of world income by \$8.1 trillion, or 0.35% of discounted income. This is equivalent to an annuity of \$403 billion per year at a 5% annual discount rate. Imposing the 2 °C temperature constraint is quite costly, reducing the net benefit by almost half, because of the difficulty of attaining that target with so much inertia in the climate system. The Copenhagen Accord with phased-in participation of developing countries has substantial net benefits, but lack of participation in the "rich-only" case reduces these substantially. Fig. 4 shows the path of net costs as a percentage of income for seven major regions. Costs rise gradually over the coming decades and reach around 1% of national income for the high-income countries in the mid-21st century.

There are many conclusions that can be drawn from the present modeling effort. One important result is that even if countries meet their ambitious objectives under the Copenhagen Accord, global temperatures are unlikely to keep within the objective of 2 °C. This conclusion is reinforced if developing countries delay their full participation beyond the 2030–2050 time frame.

**Comparisons with Other Studies.** The results here can be compared with those of earlier versions of the RICE model as well as with those of other modeling groups. The details of the comparisons are available in *SI Appendix*. The temperature projections of the RICE-2010 model are substantially similar to those of the earliest vintages (*SI Appendix*, Fig. S3). The damage ratio (ratio of climate damage to output) is similar to that found in earlier versions for the first century, but the latest version projects higher damage ratios in the more distant future because of the inclusion of SLR (*SI Appendix*, Fig. S4). The optimal carbon price in the near term is substantially higher than in earlier versions (*SI Appendix*, Fig. S5). For example, that price for 2015 is ≈\$40 per ton carbon, whereas in the early vintages, the optimal carbon price was in the \$10–15 range. The major factors accounting for this difference are a major upward revision of global output with adoption of purchasing-power parity income measurement, higher temperature sensitivity, and lower discount rate on goods (25).

The results can also be compared with the latest round of model comparisons done for the Energy Modeling Forum 22 (EMF-22) (14). The closest comparison is the path of $CO_2$ concentrations for the 2000–2100 period for the RICE baseline and EMF-22 reference path. The RICE-model concentrations path is above the median of the 10 models with complete data. For the terminal year of 2100, the 10th, 50th, and 90th percentiles of $CO_2$ concentrations for the EMF-22 are 643, 754, and 910 ppm, whereas the RICE-model projection for 2100 is 793 ppm (a more detailed comparison is provided in *SI Appendix*, Fig. S6). The EMF-22 projections also indicate the difficulty of attaining the 2 °C objective (14).

Note that the optimal carbon prices in the RICE model are well below those in studies with very low discount rates, particularly those in the Stern Review (26, 27). Discussions about discounting involve unresolved issues of intergenerational fairness, aversion to inequality, and projections about future technological change and population growth as well as the appropriateness of the utilitarian framework used in the Ramsey model (5, 28, 29).

Another important area for analysis is the uncertainty associated with projections and policy analysis. Integrated assessment models are useful in making estimates of systemic uncertainty because they can incorporate all elements of the model and parameters. Estimating uncertainties and the benefits of better scientific knowledge is an important item on the research agenda (25).

**Table 1. Carbon prices in the different runs**

| | 2005 prices per ton of carbon | | | | | | |
|---|---|---|---|---|---|---|---|
| Carbon prices | 2005 | 2010 | 2015 | 2020 | 2025 | 2055 | 2105 |
| Optimal | 0.00 | 28.90 | 37.96 | 49.87 | 65.50 | 155.55 | 408.48 |
| Limit temperature change <2 °C | 0.00 | 58.92 | 79.04 | 106.03 | 142.25 | 521.78 | 903.69 |
| Copenhagen: full trade | 0.00 | 0.10 | 0.39 | 1.51 | 5.79 | 358.37 | 593.10 |
| Copenhagen: rich only | 0.00 | 0.07 | 0.39 | 2.21 | 12.40 | 64.11 | 27.68 |

The carbon prices are the market prices that are required to attain the policy objectives. These assume full trading and participation in all regions that are in the policy regime.

**Table 2. Present value of consumption, different policies (scaled to 2005 US international dollars, 2005 prices)**

| Policy scenario | Present value utility Trillions of 2005 $ | Difference | | Annualized* Billions of $ per year |
|---|---|---|---|---|
| | | Trillions of 2005 $ | Percentage of base | |
| Base | 2,301.5 | 0.00 | 0.00% | 0 |
| Optimal | 2,309.6 | 8.06 | 0.35% | 403 |
| Limit temperature change <2 °C | 2,305.9 | 4.37 | 0.19% | 219 |
| Copenhagen: full trade | 2,307.8 | 6.26 | 0.27% | 313 |
| Copenhagen: no trade | 2,307.1 | 5.63 | 0.24% | 281 |
| Copenhagen: rich only | 2,304.1 | 2.55 | 0.11% | 128 |

The estimates are the present value of consumption equivalent for the entire period. The difference in numerical column 2 shows the difference between the control run and the no-policy or baseline run. Incomes of countries are calculated using purchasing-power parity exchange rates and are discounted using an international interest rate that is the capital-weighted average of the real interest rates for different regions.

*Annual value of consumption at a discount rate of 5% per year.

## Cautionary Notes

Analyses using integrated assessment economic models present an unrealistically smooth picture of the functioning of economic and political systems in much the same way that global climate models cannot capture the turbulence of weather systems. I conclude with four cautionary observations about the difficulties that arise in forging effective programs to slow climate change.

A first issue arises because of the strategic relationship between costs of abatement (which are thoroughly local) and avoidance of climate damage (which is a widely dispersed Samuelsonian public good). This structure of local costs and dispersed benefits leads to strong incentives to free riding: Each country has little incentive to take action and will benefit greatly if everybody else abates. This situation is analyzed using the Nash equilibrium concept from game theory. A Nash, or noncooperative, equilibrium results when no player can find a strategy to improve his or her payoff assuming that the other players stick to their strategies (30). A Nash equilibrium does not rule out any climate-change policies. Rather, noncooperative behavior implies that countries take abatement actions only to the extent that they themselves benefit and the benefits to the rest of the world are ignored.

Earlier studies have found that a Nash equilibrium would lead to carbon prices and emissions reductions that are much lower than optimal (17, 31, 32). Similar results are found in the RICE-2010 model. If we assume that each of the 12 regions acts noncooperatively, carbon prices are calculated to be approximately 1/10th of the optimal levels (*SI Appendix*, Table S8). (This may actually overstate noncooperative abatement because it assumes that countries within large regions such as Latin America coordinate their strategies.) The strategic significance of this finding is that countries will have strong incentives to free ride by not participating or to "cheat" on strong climate-change agreements. If they hide emissions or overstate reductions, their own economic welfare will improve even though others' welfare will deteriorate.

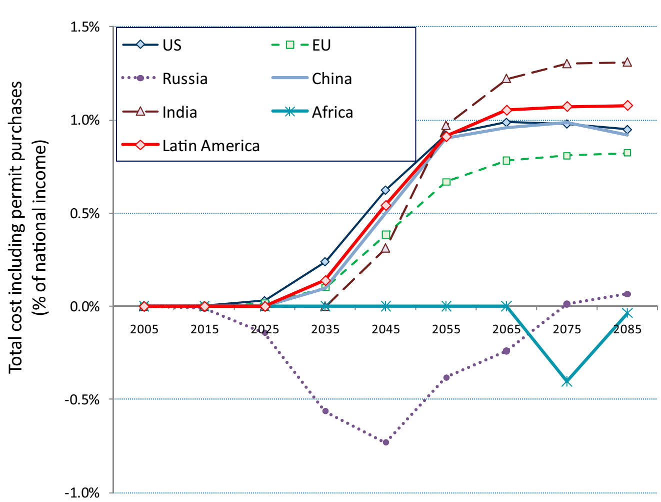


**Fig. 4.** Total costs of compliance as percent of national income. EU, European Union.

The difficulty of escaping from a low-level noncooperative equilibrium is amplified by a second factor, the intertemporal tradeoff. Climate-change policies require costly abatement in the near term to reduce damages in the distant future. The generational tradeoff is shown in Table 3. The last line shows the difference in global discounted damages and discounted abatement costs through 2055 between the outcome under the Copenhagen Accord and that in the baseline scenario. Abatement costs are more than five times the averted damages. For the period after 2055 (not shown), however, the ratio is reversed: Damages averted are more than four times abatement costs. Asking present generations—which are, in most projections, less well off than future generations—to shoulder large abatement costs would be asking for a level of political maturity that is rarely observed. The delayed payoffs reinforce the incentives of the noncooperative equilibrium, so the temptation is high to postpone taking the costly steps to reduce emissions.

A third issue arises because of the spatial asymmetry between winners and losers among countries. The trajectory of net costs for selected countries is shown in Fig. 4, and the numerical net costs in 2055 are shown in the last column of Table 3. The regions designated to undertake the largest emissions reductions under the Copenhagen Accord are the United States, China, and the European Union: The price tag for these regions totals more than $1 trillion in discounted costs through 2055. Several other regions, particularly Russia, can expect net benefits in a trading regime because they have been allocated excess emissions permits. Although poor countries can present reasoned arguments why rich countries should take the major emissions cuts, rich countries will weigh their own costs and attempt to share the burden more widely. This asymmetry reinforces the tendency of countries to move to their noncooperative equilibrium, resulting in an "aprés vous" syndrome in which no country takes substantial steps.

A final difficulty arises because the Kyoto and Copenhagen regimes have adopted a cap-and-trade structure. These have the theoretical advantage that they can coordinate emissions reductions across countries in an efficient manner. However, these theoretical advantages have proved illusory to date. Analysts who have examined the actual functioning of similar quantitative restrictions in different sectors note many difficulties with cap-and-trade that are not fully appreciated in the scientific community (33, 34). Economists often point to harmonized carbon taxes as a more efficient and attractive regime, but these have been generally

**Table 3. Costs and benefits of Copenhagen Accord through 2055**

| | Costs and benefits (billions of US dollars, discounted through 2055) | | | |
|---|---|---|---|---|
| Region | Change in damages | Abatement costs | Permit purchases | Net costs |
| United States | −51 | 328 | 228 | 505 |
| European Union | −56 | 160 | 171 | 276 |
| Japan | −12 | 44 | 64 | 96 |
| Russia | −5 | 92 | −176 | −89 |
| Eurasia | −4 | 62 | −150 | −92 |
| China | −52 | 655 | −268 | 335 |
| India | −54 | 185 | −1 | 130 |
| Middle East | −47 | 123 | −134 | −57 |
| Africa | −41 | 0 | 0 | −41 |
| Latin America | −33 | 127 | 154 | 248 |
| OHI | −18 | 96 | 48 | 126 |
| Other | −42 | 188 | 64 | 209 |
| World | −413 | 2,060 | 0 | 1,647 |

The table illustrates the regional asymmetry of the Copenhagen Accord. The estimates take the present value of abatement costs and averted damages using the capital-weighted international real interest rate. The last column is the sum of the first three columns. OHI, other high income.

shunned in negotiations, particularly in the United States, because of the taboo on considering tax-based systems (35).

The results of the present study suggest that several policies could limit our "dangerous interference" with the climate system at modest costs. However, such policies would require a well-managed world and globally designed environmental policies, with most countries contributing, with decision makers looking both to sound geosciences and economic policies. Moreover, rich countries must bring along the poor, the unenthusiastic, and the laggard with sufficient carrots and sticks to ensure that all are on board and that free riding is limited. The checkered history of international agreements in areas as diverse as finance, whaling, international trade, and nuclear nonproliferation (36) indicates the extent of the obstacles on the road to reaching effective international agreements on climate change.

**ACKNOWLEDGMENTS.** I am grateful for the research assistance of Xi Chen and Mark Longhurst. This study is the product of collaborative work on earlier versions of the RICE model with Zili Yang and Joseph Boyer. Comments and suggestions from colleagues in the field have been essential to the improvements in the model, and I am grateful for the valuable comments of reviewers. This research has been supported by the National Science Foundation, the US Department of Energy, and the Glaser Foundation.

1. Revelle R, Suess HE (1957) Carbon dioxide exchange between atmosphere and ocean and the question of an increase of atmospheric $CO_2$ during the past decades. *Tellus* 9:18–27.
2. Samuelson PA (1954) The pure theory of public expenditure. *Rev Econ Stat* 36:387–389.
3. United Nations (1992) United Nations Framework Convention on Climate Change, article 2. Available at http://unfccc.int/resource/docs/convkp/conveng.pdf. Accessed February 19, 2010.
4. United Nations (2009) Copenhagen Accord. Available at http://unfccc.int/resource/docs/2009/cop15/eng/l07.pdf. Accessed February 19, 2010.
5. Ramsey FP (1928) A mathematical theory of saving. *Econ J* 38:543–559.
6. Koopmans TC (1963) On the concept of optimal economic growth. Cowles Foundation Discussion Papers. Yale University. Available at http://cowles.econ.yale.edu/P/cd/d01b/d0163.pdf. Accessed February 19, 2010.
7. Nordhaus WD (1994) *Managing the Global Commons: The Economics of Climate Change* (MIT Press, Cambridge, MA).
8. Arrow KJ, et al. (1995) Intertemporal equity, discounting, and economic efficiency. *Climate Change 1995: Economic and Social Dimensions of Climate Change, Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, eds Bruce J, Lee H, Haites E (Cambridge Univ Press, Cambridge, UK), pp 125–144.
9. United Nations (2004) *World Population to 2300. Department of Economic and Social Affairs, Population Division, United Nations, ST/ESA/SER.A/236* (United Nations, New York).
10. International Monetary Fund (2009) *World Economic and Financial Surveys, World Economic Outlook Database, April 2009* (IMF, Washington).
11. World Bank (2009) *World Development Report, World Development Report Database* (World Bank, Washington).
12. Nordhaus WD, Boyer J (2000) *Warming the World: Economic Modeling of Global Warming* (MIT Press, Cambridge, MA).
13. Intergovernmental Panel on Climate Change (2007) *Climate Change 2007: Mitigation of Climate Change, Working Group III Contribution to the Intergovernmental Panel on Climate Change* (Cambridge Univ Press, Cambridge, UK).
14. Clarke L, Böhringer C, Rutherford TF (2009) International, U.S. and E.U. climate change control scenarios: Results from EMF 22. *Energy Economics* 31(Suppl 2): S63–S306.
15. Metz B, et al., eds (2005) *IPCC Special Report on Carbon Dioxide Capture and Storage* (Cambridge Univ Press, Cambridge, UK).
16. Hotelling H (1931) The economics of exhaustible resources. *J Polit Econ* 39:137–175.
17. Nordhaus WD, Yang Z (1996) A regional dynamic general-equilibrium model of alternative climate-change strategies. *American Economic Review* 86:741–765.
18. Hansen J, et al. (2009) Global temperature change. *Proc Natl Acad Sci USA* 103: 14288–14293.
19. Intergovernmental Panel on Climate Change (2007) *Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the IPCC* (Cambridge Univ Press, Cambridge, UK).
20. Tol R (2009) The economic effects of climate change. *J Econ Perspect* 23:29–51.
21. Intergovernmental Panel on Climate Change (2007) *Climate Change 2007: Impacts, Adaptation and Vulnerability, Working Group II Contribution to the Intergovernmental Panel on Climate Change, Summary for Policymakers* (Cambridge Univ Press, Cambridge, UK).
22. Oppenheimer M (1998) Global warming and the stability of the West Antarctic Ice Sheet. *Nature* 393:325–332.
23. Oppenheimer M, Alley RB (2004) The West Antarctic Ice Sheet and long term climate policy. *Clim Change* 64:1–10.
24. National Research Council, Committee on Abrupt Climate Change (2002) *Abrupt Climate Change: Inevitable Surprises* (National Academy Press, Washington).
25. Nordhaus WD (2007) *A Question of Balance: Economic Models of Climate Change* (Yale Univ Press, New Haven, CT).
26. Stern N (2006) *The Economics of Climate Change: The Stern Review* (Cambridge Univ Press, Cambridge, UK).
27. Dietz S, Hope C, Stern N, Zenghelis D (2007) Reflections on the Stern Review, a robust case for strong action to reduce the risks of climate change. *World Economics* 8: 121–168.
28. Nordhaus W (2007) A review of the Stern Review on the economics of climate change. *Journal of Economic Literature* 45:606–782.
29. Sen A, Williams B, eds (1982) *Utilitarianism and Beyond* (Cambridge Univ Press, New York).
30. Nash JF (1950) Equilibrium points in *n*-person games. *Proc Natl Acad Sci USA* 36:48–49.
31. Yang Z (2007) *Strategic Bargaining and Cooperation in Greenhouse Gas Mitigations: An Integrated Assessment Modeling Approach* (MIT Press, Cambridge, MA).
32. Carraro C, Egenhofer C (2008) *Climate and Trade Policy: Bottom-Up Approaches Towards Global Agreement* (Edward Elgar, Cheltenham, UK).
33. Cooper RN (1998) Toward a real global warming treaty. *Foreign Aff* 77:66–79.
34. Nordhaus WD (2007) To tax or not to tax: Alternative approaches to slowing global warming. *Review of Environmental Economics and Policy* 1:26–44.
35. Metcalf GE (2009) Designing a carbon tax to reduce U.S. greenhouse gas emissions. *Review of Environmental Economics and Policy* 3:63–83.
36. Cooper RN, et al. (1989) *Can Nations Agree?* (Issues in International Economic Cooperation, Brookings Institute, Washington).