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Author(s): Thomas C. Schelling

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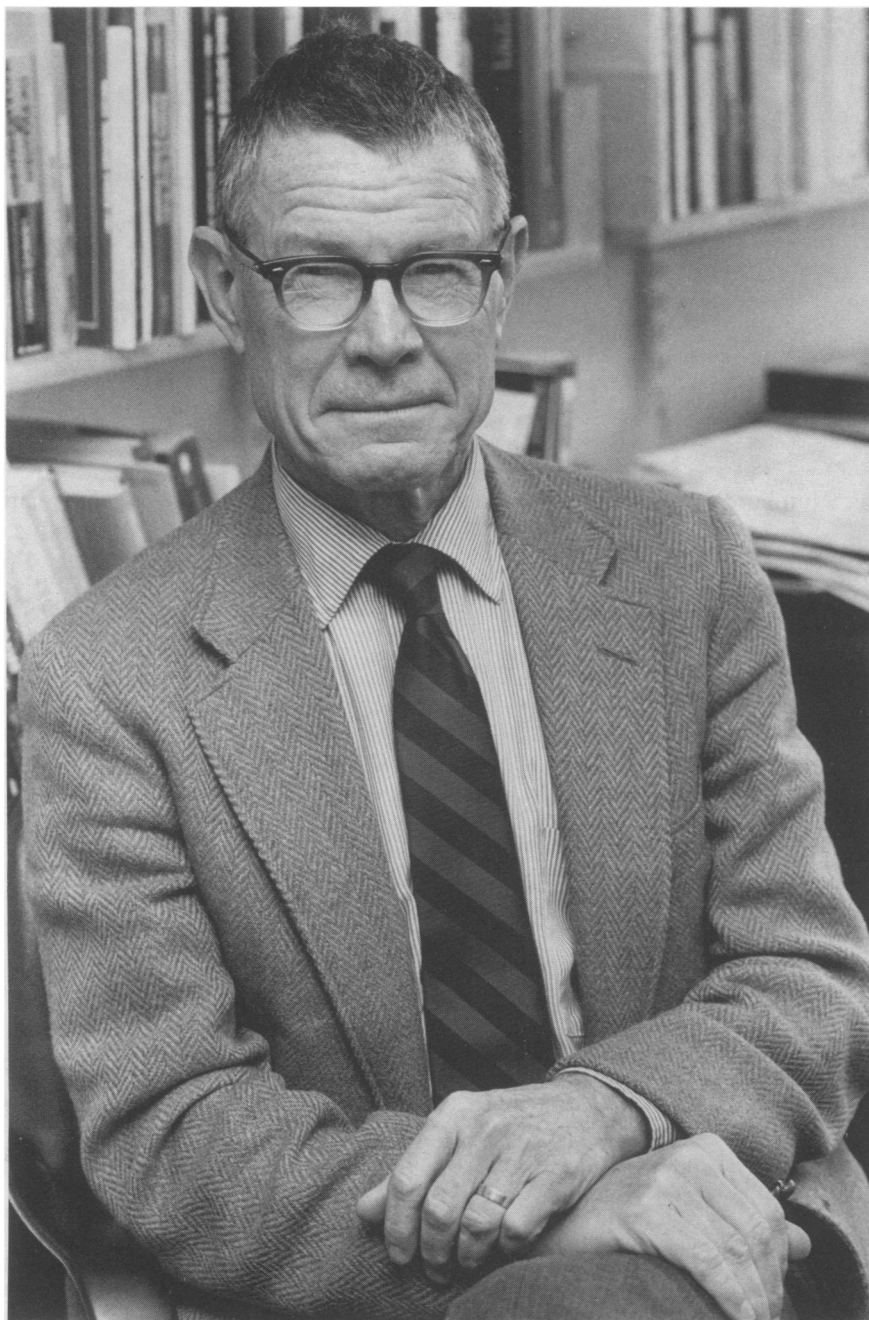
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Some Economics of Global Warming

By THOMAS C. SCHELLING*

Global warming from carbon dioxide was an esoteric topic 15 years ago, unknown to most of us. But in a few years, helped along by some hot summers, it has climbed to the top of the international agenda. Cabinets, Parliaments, and heads of government have issued pronouncements on reducing carbon emissions, and in June of this year more than a hundred governments will be represented by ministers or heads of government at a great United Nations Conference on Environment and Development to be held in Rio de Janeiro. Together with non-governmental organizations representing labor, business, students, environmentalists, scientists, and groups concerned with health and child development and family planning, these representatives are expected to need 25,000 hotel rooms. A "framework agreement" is widely expected, together with some institutional arrangements that will keep global environmental issues permanently on every government's agenda. And at the center of these issues will be the phenomenon that has come to be known as the "greenhouse effect."

The greenhouse effect itself is simple enough to understand and is not in any real dispute. What is in dispute is its magnitude over the coming century, its translation into changes in climates around the globe, and the impacts of those climate changes on human welfare and the natural environment. These are beyond the professional understanding of any single person. The sciences involved are too numerous and diverse. Demography, economics, biology, and the technology sciences are needed to project emissions; atmospheric chemistry, oceanography, biology, and meteorology are needed to translate emissions into climates;

biology, agronomy, health sciences, economics, sociology, and glaciology are needed to identify and assess impacts on human societies and natural ecosystems. And those are not all.

There are expert judgments on large pieces of the subject, but no single person clothed in this panoply of disciplines has shown up or is likely to. So, I venture to offer my judgment.

I

First on the principle. The metaphor of the greenhouse is not quite appropriate, but the basic idea is not in dispute. The earth is bathed in sunlight, some reflected and some absorbed. If the absorption is not matched by radiation back into space, the earth gets warmer until the intensity of that thermal radiation matches the absorbed incoming sunlight. Some gases in the atmosphere that are transparent to sunlight absorb radiation in the infrared spectrum, blocking that outward radiation and warming the atmosphere. When the atmosphere has warmed enough to intensify the thermal radiation so that it matches the absorbed incoming sunlight, equilibrium is achieved at the higher temperature. These so-called "greenhouse" gases can be identified in the laboratory. Carbon dioxide is one of them; methane is another, as is nitrous oxide, as are the chlorofluorocarbons (CFC's).

The principle has been in practice for decades. On a clear day in January, the earth and its adjacent air in Orange County California warm nicely, but the warmth radiates rapidly away during the clear nights, and frost may threaten the trees. Smudge pots, burning cheap oil on a windless night, produce substances, mainly carbon dioxide, that absorb the radiation and protect the trees with a blanket of warm air. Greenhouses, in contrast, mainly trap the air warmed by the earth's surface and keep it

*Department of Economics, University of Maryland, College Park, MD 20742.

from rising to be replaced by cooler air. The phenomenon should have been called the "smudgepot effect," but it is too late to do anything about it.

A first step in pursuing this phenomenon is to assess how much warming might go with an enhanced concentration of these gases. That cannot be done in the laboratory; there are too many feedbacks. A warmer atmosphere will contain more water vapor; water vapor itself is a greenhouse gas. Changes in temperature and humidity will change cloud cover; clouds can reflect or absorb incoming or outgoing light according to their composition and altitude. The average temperature is only one dimension; temperatures at different altitudes and different latitudes matter. But a starting point has been the change in average surface atmospheric temperature expected to accompany a specified increase in the concentration of greenhouse gasses; and arbitrarily, but reasonably, the base case is taken as a doubling of the concentration.

A moment on why a doubling is the benchmark. To compare estimates of warming, people must use the same hypothesized concentration of greenhouse gases in the atmosphere. (Alternatively, they could use the same hypothesized temperature increase and estimate the corresponding concentration.) Doubling, like a half-life in reverse, is a natural unit if it is within the range of practical interest, and it is. A doubling is expected sometime in the next century, so it is temporally relevant; and a doubling is estimated to make a substantial but not cataclysmic difference. If fixation on a doubling seems to imply an upper limit on any expected increase, the implication is unfortunate: enough fossil fuel exists to support several doublings.

In 1979, a committee of the National Academy of Sciences (NAS) (1979 p. 2) estimated the change in average temperature to accompany a doubling of carbon dioxide in the atmosphere: three degrees Celsius, with a range of 1.5 degrees to either side. (In the last 15 years other greenhouse gases have received attention; these other gases can be converted to their car-

bon dioxide equivalents and the original estimate applied to the mixture.) The NAS appointed another committee a few years later to reexamine that estimate, and the new committee saw no reason to change it (NAS, 1982 p. 51). An intergovernmental panel on climate change (IPCC), consisting of scientists from many nations, revisited the estimate in 1990 and concluded, from the several climate models they had examined, that "the models results do not justify altering the previously accepted range of 1.5 to 4.5 degrees C" (IPCC, 1990 p. xxv). Thus, the estimate appears to be robust over time, but the spread of uncertainty remains large: the upper limit is three times the lower limit. (No quantitative interpretation of these upper and lower "limits" has been made public. Both National Academy reports referred to them as "probable error.")

II

The uncertainties are even greater in translating a temperature change into climates. The media support a popular view that things will just get hotter; a news magazine cover was a sweating global face. But the laboratories that do the meteorology do not simply predict warming; they do not even predict that the most noticeable effects will necessarily be temperature changes. Among the great driving forces of weather and climate is the temperature differential between equatorial and polar regions; convection currents coupled with the rotation of the earth are engines of atmospheric circulation and, ultimately, ocean circulation. The models predict greater temperature change in the polar regions than near the equator. This change in gradient can drive changes in circulation. The results may be warmer in some places and colder in others, wetter in some places and drier in others, cloudier in some places and sunnier in others, stormier in some places and less stormy in others—generally a complex of changes that would bear no easy relation to an average change in global temperature.

The change in average temperature is useful as an *index* of climate change. It is

thought, and the models demonstrate, that the greater the change in average temperature the greater the departure of current climates from what they are now. Thus, while it is wrong to think that what is going to happen can be readily characterized as “warming” it is not erroneous to take that average warming as a rough measure of the extent or severity of change to be expected. Unfortunately the widespread reference to “global warming” promotes the notion that things will simply get hotter. (Interestingly, virtually all public discussion is on hotter summers, not warmer winters; a hundred years ago popular discussion of a warming trend would likely have concentrated on the milder winters to be expected.)

If three degrees Celsius is taken as an index of climate change to come within the next century or so, how big is that compared with what has happened within the last century, or the last 10,000 years? From what I have just said, this cannot be answered in terms of whether anyone would notice the difference if every night and every morning, every winter and every summer, temperatures were exactly three degrees higher than they otherwise would have been. The question is: how would a three-degree change in a global average compare with what has been experienced in the past?

The answer is that for 10,000 years, since the disappearance of the last ice age, average temperature appears never to have varied over anything like three degrees. A band of one degree Celsius would cover the current estimates of what average temperatures have been since the dawn of recorded history. We will be moving into a climatic regime that has never been experienced in the current interglacial period.

“Mankind will undergo greater climate change in the next 100 years than has been experienced in the last 10,000.” Properly qualified, the statement is true; what it neglects is that peoples have been migrating over great distances for at least several thousand years. Goths and Vandals, Huns, West Europeans who populated North and South America, Southerners who went North during the Great Depression, and

Northeasterners who moved southwest after World War II all experienced changes in climate greater than any being forecast by the models. Almost everybody who attends this lecture in New Orleans will have undergone a greater change in the past few days than is expected to occur in any fixed locality during the coming century.

The changes that the models produce are *gradual* both in time and in space. The models do not produce discontinuities. Climates will “migrate” slowly. The climate of Kansas may become like Oklahoma’s, Nebraska’s like that of Kansas, South Dakota’s like Nebraska’s, but none of these is expected to become like the climates of Oregon, Louisiana, or Massachusetts.

A caution: the models probably cannot project discontinuities—just gradual change—because nothing goes into the models that will produce *catastrophes*. There may be phenomena that could produce drastic change, but they are not known with enough confidence to introduce them into the models. So the reassuring gradualness may be an artifact of the methodology. I will return to this point later.

This greenhouse problem, if problem it proves to be, is truly one of the “global common.” A ton of carbon emitted anywhere on earth has the same effect as a ton emitted anywhere else. And carbon dioxide has a long residence time in the atmosphere: a century or more. There may be ways to remove it, but it doesn’t disappear. The greenhouse influence on any national territory depends solely on the global concentration, not in any way on what part of the total is due to a nation’s own emissions.

As I shall detail later, the costs of reducing carbon emissions will be large compared with any other emissions that have caused concern. The costs of phasing out CFC’s will be in the billions of dollars per year for some years, and complete elimination is expected to be feasible. The cost of reducing sulfuric acid may be in the tens of billions of dollars. Proposals to hold emissions of carbon dioxide constant (with a linear increase of concentration in perpetuity) or to reduce emissions by 50 percent below what they

would otherwise be, beginning perhaps in 2010, are expected to cost in the hundreds of billions in perpetuity.

There are a few numbers worth carrying in mind. There are 700 billion tons of carbon in the atmosphere. (Quotations are sometimes in tons of carbon dioxide, rather than carbon; the figure is then $3\frac{2}{3}$ times as large, about 2,600 billion.) Annual emissions are 6 billion tons. Close to half disappears somewhere, and a little over half remains in the atmosphere; so the concentration is increasing by one-half percent per year. It has increased 25 percent in the last hundred years. (Concentration is reported more often than tonnage; it is currently about 350 parts per million.) And there are upwards of ten trillion tons of carbon fuels out there to be burned; if it were all burned and half stayed in the atmosphere, the concentration could double at least three times.

If the carbon in the atmosphere has already increased by a quarter, has the average temperature gone up as predicted? And were the recent hot American summers that stirred popular interest harbingers of greenhouse summers to come?

To the first question, the answer is that average global temperature—summer and winter, both hemispheres, night and day—has apparently risen by half a degree in the last hundred years, but whether “as predicted” depends on what qualifications one reads into the predictions. The pattern differed between the Northern and Southern Hemispheres. The global average rose during the first 40 years of this century, was level for the next 40 years, and rose during the past decade. This pattern demonstrates that, whether or not we are witnessing the greenhouse effect, there are other decades-long influences that can obscure any smooth greenhouse trend. (The carbon concentration is not at issue; it is well measured and shows steady rise on a decade scale.) There are known phenomena that could account for the irregular temperature increase of the past century, and whether we are witnessing the “signal” probably depends on whether one wants high confidence to reject a null hypothesis or is about to bet money on whether, another 25 years from now,

looking back, all doubt will have been removed. I don’t know what bets are being placed by “greenhouse scientists,” but they are cautious in public on the question.

To the second question—do the hot American summers of the past few years announce the arrival of a greenhouse, confirming predictions?—the answer is in two parts: maybe it’s the greenhouse; but it’s not what the greenhouse models predict. The global average in the four hot years of the past seven was only 0.2 degrees above the level of the preceding 40 years; and sudden hot American summers are not what the models predict.

III

In anticipating the impact on human welfare or natural systems, two kinds of uncertainty are unlikely to be dispelled soon. One is simply the question of what the changes will be in each region or locality. Current models are severely limited in their agreement with each other, in their handling of such topographical variables as mountain ranges, and in the fineness of the grids they superimpose on the globe. There is no great confidence that the models will be greatly improved within the next decade or two. A chaos-like process may defeat efforts to improve local predictions; and uncertainties in gross phenomena, such as the behavior of ocean currents under changed climatic conditions, may not be much better understood soon.

Even if we had confident estimates of climate change for different regions of the world, there would still be uncertainties about the kind of world it is going to be 50, 75, or 100 years from now. Imagine it were 1900 and the climate changes associated with a three-degree average temperature increase were projected to 1992. On what kind of world would we superimpose either a vaguely described potential change in climate or even a specific description of changes in the weather in all the seasons of the year, even for our own country. There would have been no way to assess the impact of changing climates on air travel, electronic communication, the construction of

skyscrapers, or the value of California real estate. Most of us worked outdoors; life expectancy was 47 years (it is now 75); barely a fifth of us lived in cities of 50,000 or more. Anticipating the automobile, we might have been concerned with whether wetter and drier seasons would bring more or less mud, not anticipating that the nation's roads would become thoroughly paved. The assessment of effects on health would be without antibiotics or inoculation. And in contrast to most contemporary concern with the popular image of hotter summers to come, I think we would have been more concerned about warmer winters, later frost in autumn, and earlier thaw in the spring.

If the world, both North America and the other continents, is going to change as much in the next 90 years as it has changed in the 90 just past, we are going to be hard put to imagine the effects of climate changes.

Another thought experiment: suppose the kind of climate change expected between now and, say, 2080 had already taken place since 1900. Ask somebody 50, 60, or 80 years old what is different compared with when he or she was a child. Would the climate change be noticed? Even ask a 70-year-old farm couple living on the same farm where they were born: would the change in climate be among the most dramatic changes in either their farming or their lifestyle? I expect changing from horses to tractors and from kerosene to electricity, the arrival of the telephone and the automobile and the paving of roads, the development of pesticides and artificial fertilizer, the discovery of soy beans and the development of hybrid corn, and even improvements in outdoor clothing, veterinary medicine, and agricultural practices generally would swamp the climate change. And if instead of living and working conditions we inquire about changes in wildlife and natural ecosystems, changes in regional climates would have been competing, in their impact on nature, with population growth and economic development.

A conclusion we might reach is that a climate change would have appeared to make a vastly greater difference to the way people lived and earned their living in 1900

than to the way people live and earn their living today. Today very little of our gross domestic product is produced outdoors, susceptible to climate. Agriculture and forestry account for less than 3 percent of GDP, and little else is much affected. Some activities—tourism and holidays, professional sports, and school teaching—are seasonal, but many of the seasonalities are conventions that reflect the influence of climate in earlier times. (Children were needed in the fields in summer and could start school when the harvest was in; hockey and basketball used to be winter sports because one depended on ice and the other could fit in a building.)¹

Manufacturing rarely depends on climate, and where temperature and humidity used to make a difference, air conditioning has intervened. When Toyota chooses among Ohio, Alabama, and Southern California for locating an automobile assembly, geographical considerations are important, but not because of climate. Minerals are extracted where they happen to occur, and oil fields and coal mines inhabit all kinds of climates and are little affected. The U.S. Postal Service's vow that neither snow nor rain nor heat nor gloom of night will "stay these couriers from the swift completion of their appointed rounds" sounds quaint in the era of e-mail and fax.

Finance is little affected by climate; similarly for health care, or education, or broadcasting. Transportation can be affected, but improvements in all-weather landing and take-off in the last 30 years are greater than any differences that climate makes. If the average effect is a warming, iced waterways and snow removal may decline in importance. Construction is affected, mainly by cold, and if the average effect is in the direction of warming, construction may benefit slightly.

It is really agriculture that is affected. But even if agricultural productivity declined by a third over the next half century, the per

¹An imaginative discussion is in Jesse H. Ausubel (1991).

capita GNP we might have achieved by 2050 we would achieve only in 2051. Considering that in most of the developed countries—the United States, Japan, France, the United Kingdom, the Netherlands, and Israel—the agricultural problem has been protecting farmers, that agricultural productivity in most parts of the world continues to improve, and that many crops and cultivated plants will benefit directly from enhanced photosynthesis due to increased carbon dioxide, one cannot be certain that the net impact on agricultural productivity will be negative or, if negative, will be noticed in the developed world.

I conclude that in the United States, and probably Japan, Western Europe, and other developed countries, the impact on economic output will be negligible and unlikely to be noticed.² And there is no reason to believe that in these countries there could be a noticeable impact on health. Any influence of climate on health in this country would be more in the regional distribution of the population than in changes in local and regional climates.

Comfort is worth considering. Fortunately, the climate models predict a greater warming in winter than in summer. Most people in the United States, Japan, and Western Europe go south for vacation, both summer and winter; and when people move upon retiring in the United States they typically move toward warmer climates. In future years, elderly people may suffer more heat stroke in summer in St. Louis, but we can hope for fewer broken bones from ice in Boston. (Inhaling air richer in carbon dioxide has no effect on health.)

IV

This complacent assessment cannot be extended to the much larger population of the underdeveloped world. The livelihoods earned in agriculture and other climate-

sensitive outdoor activities, 3 percent in the United States, comprise 30 percent and more of all livelihoods in most of the developing world. Reliable forecasts of likely climate changes in the different areas so dependent on agriculture are simply not available, so no assessment, region by region, of the effect on productivity can be provided. There is no strong presumption that the climates prevailing in different regions 50 or 100 years from now will be less conducive to food production. But there is also no assurance that climate changes will not be harmful, and even if on balance the impact is neutral, there may be large areas with large populations that suffer severely. Those people are vulnerable in a way that Americans, Western Europeans, and Japanese are not.

Nor can the impact on health be dismissed or readily subsumed among generally improving health conditions, as for the developed world. Numerous parasitic and other vector-borne diseases affecting hundreds of millions of people are sensitive to climate. Again, there is no strong presumption that malaria mosquitos, to take an example, will on balance benefit from climate changes, but the risk is there.

It is with the less-developed countries that we have to be most careful about superimposing the climates of the future on the economies and societies of today. As it was in our own country during this century, the trend in developing countries is to be less dependent on agriculture and less vulnerable to climate in transportation and other activities and health. If per capita income growth in the next 40 years compares with the 40 years just past, vulnerability to climate change should diminish, and the resources available for adaptation should be greater. I say this not to minimize concern about climate change, but to anticipate the question of whether developing countries should make sacrifices in their development to minimize the emission of gases that may change climate to their disadvantage. Their best defense against climate change may be their own continued development.

This is a point worth emphasizing. Some environmentalists argue that developing

²A comprehensive discussion of both impacts and costs of abatement is provided by William D. Nordhaus (1991a). A carefully argued opposing view is that of William R. Cline (1992).

countries should sacrifice some of their hopes for economic development in the interest of slowing the climate change that may prove disastrous. But the advice contains a contradiction. Any disaster to developing countries from climate change will be a disaster to their economic development. What is desired is to optimize development by investing in greenhouse-gas abatement only when that appears, subject to all the uncertainties, to contribute more to their development in the future than the alternative direct investment in development. It is not economic growth versus environment; it is growth with the environment taken into account.

A related point: population growth is important for the climate change, in two respects. One is that carbon emissions in developing countries are positively driven by population; population growth does not merely dilute carbon emissions per capita, but for a number of reasons more people means more carbon. If China succeeds in holding population growth to near zero for the next couple of generations, it may do as much for the earth's atmosphere as would a heroic Chinese anticarbon program coupled with 2-percent annual population growth.

The other population effect is simply that the most likely adverse impact of climate change on human productivity and welfare would be on food production. In the poorest parts of the world, the adequacy of food depends on the number of mouths and stomachs. In a hundred years, adverse changes in climate for food production would be far more tragic if the countries we now associate with the developing world had populations totaling 12 billion than if they totaled 9 billion. For the developing world, the increasing concentration of people is probably more serious than the increasing concentration of carbon dioxide.

At this point, I appear to have reached the conclusion that the *developed* world has no self-interest in expensively curtailing carbon consumption and that the *developing* world cannot afford to incur economic penalties to slow the greenhouse effect. There is a mismatch between those who may be vulnerable to climate change and

those who can afford to do anything about it.

V

Why should the rich developed countries care enough about climate change to do anything about it? The answer must depend partly on how expensive it is going to be to do anything about it. Abatement programs have been examined in a number of econometric models that suggest we might want to treat as pertinent the sacrifice of perhaps 2 percent of world GNP in perpetuity.

A strong argument for trying seriously to slow climate change is that the developing countries are vulnerable and we care. Developed countries are currently providing \$50 billion per year of assistance to the developing world; we would be talking about expending or forgoing perhaps 4–8 times that much to slow emissions and slow climate change. Whether people in the developed democracies could be mobilized to contribute so much to benefit, half a century from now, the people in the countries we now call developing I do not know, but I believe that if the developed countries were prepared to invest, say, \$200 billion per year in greenhouse-gas abatement, explicitly for the benefit of developing countries 50 years or more from now, the developing countries would clamor to receive the resources immediately in support of their continued development. There would undoubtedly be abatement opportunities so cheap that they could compete with direct aid to developing countries, but it would be hard to make the case that the countries we now perceive as vulnerable would be better off 50 or 75 years from now if 10 or 20 trillions of dollars had been invested in carbon abatement rather than in their economic development.

A second argument for an expensive program of carbon abatement is that, while our production of material goods and services may not suffer from climate change, our natural environment may be severely damaged. Natural ecosystems will be destroyed; plant and animal species will become extinct. Places of natural beauty will be degraded. Valuable chemistries of plant and

animal life will be lost before we learn their genetic secrets. And the earth itself deserves our respect. For many people, something close to religious values are at stake.

This issue is doubly difficult to assess. It is difficult to know how to value what is at risk, and it is difficult to know just what is at risk. Even if climate changes at each point in time could be predicted accurately, the impacts on natural ecosystems could not yet be determined. And the benefits of slowing climate change by some particular amount would be even more uncertain. We know that carbon fuels are not going to be discontinued; the issue is the marginal gains, from carbon abatement and a slowing of climate change, in the survival of species and ecosystems and the preservation of enjoyable environments. This is an issue that simply has not been addressed.

The third argument for spending heavily to slow climate change is that the conclusions I reported earlier may be quite wrong. I said that the climate models predict that climates will change slowly and not much; the models do not produce discontinuities, surprises, *catastrophes*. What is known about weather and climate constitutes an equilibrium system.

The possibility has to be considered that if global temperature increases, not by the median estimate of three degrees Celsius for a doubling of carbon in the atmosphere, but by four or five degrees and continues to rise beyond the doubling because carbon fuels are still in use worldwide, some atmospheric or oceanic circulatory systems may switch to alternative equilibria, producing regional changes that are both sudden and extreme.

Have any such possibilities been thought of? One that was thought of but diminished upon further investigation was the possibility that the west Antarctic ice sheet might glacially melt into the ocean and raise the sea level by 20 feet. As recently as 15 years ago, the best scientific judgment was that this could happen within 75 years as a result of global warming. This prospect naturally attracted attention, and further investigation with the help of newly available satellite sensing of glacial movement led to reassuring estimates that if that catastrophic rise in

sea level were to happen it would take at least a few hundred years and be gradual, not sudden. But there isn't any scientific principle according to which all alarming possibilities prove to be benign upon further investigation.

A currently discussed likely source of discontinuous change is in the way oceans behave. Amsterdam is north of Newfoundland, yet is warmer, courtesy of the Gulf Stream. There is some indication that in earlier interglacial periods ocean currents may have pursued different courses. If a current like the Gulf Stream, or the Japanese Current for the United States, switched into an alternative pattern, the climatic consequences might be both sudden and severe. (Paradoxically, global warming might freeze Western Europe.)

Insurance against catastrophes is thus an argument for doing something expensive about greenhouse emissions. But to pay a couple percent of GNP as insurance premium, one would hope to know more about the risk to be averted. I believe research to improve climate predictions should be concentrated on the extreme possibilities, not on modest improvements to median projections.

I said that current estimates suggest that it might cost a couple percent of GNP to postpone the doubling of carbon in the atmosphere by several decades. Is 2 percent a big number or a small one?

That depends on your perspective and on what the comparison is. In recent years 100 billion dollars per year in budgets or taxes has been a politically unmanageable magnitude in the United States. On the other hand, subtracting 2 percent from GNP in perpetuity lowers the GNP curve by not much more than the thickness of a line drawn with a number-two pencil, or to formulate it as I did earlier, it postpones the GNP of 2050 until 2051. I say this not to belittle the loss of 10 trillion dollars from the American GNP over the next 60 years, but only to point out that the insurance premium, if we choose to pay it, will not send us to the poorhouse. The proper question is whether, if we were prepared to spend 2 percent of our GNP in the interest of protecting against damage due to climate

change, we might find better use for the money.

I have mentioned one use: directly investing to improve the economies of the poorer countries. Another would be direct investment in preserving species, ecosystems, or wilderness areas. There is concern that many ecosystems could not migrate as rapidly as climate may change in the coming century; there has been little investigation of what might be done to facilitate the migration of ecosystems if the alternative is to invest 5 or 10 trillions of dollars in the reduction of carbon emissions.

VI

What can be done to reduce or offset carbon emissions? Reducing energy use and the carbon content of energy have received, I believe properly, most of the attention, especially the attention of economists. There are other possibilities to mention.

Trees store carbon. In growing, they take it out of the atmosphere. When they rot or burn it goes back into the atmosphere. A new forest will absorb carbon until it reaches maturity (i.e., maximum carbon density) in 75 or 100 years. If it then merely replenishes itself, with new growth replacing the oxidized dead trees, it holds its carbon but does not absorb more. If trees are harvested, the lumber that becomes house frames or furniture may last a hundred years or more; removing mature trees and storing them anaerobically is possible but expensive. The most recent report of the National Academy of Sciences considered that reforestation in the United States might sequester 2–3 percent of current global carbon dioxide emissions.³ The prospects for that kind of reforestation in the rest of the world are not nearly so promising, and

we should conclude that reforestation can contribute, but not greatly.

Stopping or slowing *deforestation* is important for reasons other than carbon emissions but is quantitatively more important than reforestation. Reforestation is unlikely to take up as much as 100 billion tons of carbon; deforestation, in areas where deforestation is likely, could contribute several hundred billion tons of carbon, partly because forest subsoils contain carbon typically greater than the amount in the trees themselves, and this carbon is subject to oxidation when the trees are removed.

Carbon can be “scrubbed” from stack gases, probably not with any known technology that would make such removal economically competitive with reducing emissions. (Part of the expense is disposing of sludge; where gaseous carbon might be pumped into the ocean or into underground cavities, economical disposal may prove feasible.) Parallel to reforestation is the idea of enhancing oceanic photosynthesis, by “fertilizing” the oceans, possibly with iron, if enough of the carbon residues from the enhanced growth will sink rather than remain near the surface. Experiments would probably be reversible and modest in scale; their political acceptability may be tested in the near future.

Finally—although nothing is final in a subject as new as the one we are talking about—there are numerous possibilities for putting substances or objects in orbit or in the stratosphere to reflect something like 1 percent of incoming sunlight to offset a large part of the radiation imbalance caused by greenhouse gases. Some of these are as apparently innocuous as stimulating cloud formation, and some are as dramatic as huge mylar balloons in low earth orbit. Until very recently these possibilities were nearly unmentionable, but they have recently been dignified by inclusion, along with caveats about “large unknowns concerning possible environmental side effects,” in the 1991 report of the National Academy of Sciences. I shall not pursue them here, except for two observations. First, if in decades to come the greenhouse impact begins to confirm the more alarmist expectations, and if the economic sacrifices required to reduce

³Their estimate is 10 percent of U.S. emissions at “low to moderate cost” on economically or environmentally marginal crop and pasture lands and nonfederal forest lands in the United States (National Academy of Sciences, 1991 p. 57). A review of the issues in both afforestation and deforestation by Andrew Plantinga is in Joel Darmstadter (1991); an optimistic estimate of the afforestation option is that of Robert J. Moulton and Kenneth R. Richards (1990).

emissions prove unmanageable for economic or political reasons, some of these "geoengineering" options will invite attention. Second, if they do, and especially if they prove to be within the budgetary capabilities of individual nations, international greenhouse diplomacy will be transformed.

VII

What remains nearly certain is that the main responses to the greenhouse threat will be adapting to climate as climate changes and reducing carbon emissions. (CFC's are potent greenhouse gases and, if unchecked, might rival carbon dioxide in decades to come; but international actions are making good progress and are among the cheapest ways of reducing greenhouse emissions.)

Like estimates of warming, estimates of the costs of reducing emissions require some common but arbitrary objective to be comparable. A doubling of carbon became the conventional benchmark for warming estimates; no such benchmark for reduced carbon emissions has been adopted for estimating costs. (In principle, the estimates could adopt that doubling: the issue could be formulated as the cost of retarding the doubling time by a decade, two decades, or half a century.) Most estimates take as their target a reduction of emissions either to a specified fraction of what they would be in the absence of controls, or to some fixed ratio to the emissions of 1990 or the projected emissions of 2000 or 2010. The estimates examine minimum-cost trajectories, implicitly or explicitly assuming something like a uniform tax on the carbon content of fuel as the policy instrument. They typically make some assumption about a "fallback" energy technology, at least for electricity, available at some price in some decade of the next century. They have to project estimates of non-price-induced improvements in the use or avoidance of energy by industries and households. And if they deal with global emissions, they have to make some assumption about the distribution of abatement efforts among nations, especially among the developing countries, which, including China, account for about a quarter

of emissions now and would be expected to account for half by the middle of the next century.

Any estimate of the cost of abatement needs therefore to specify at least half a dozen target assumptions. Furthermore, the estimates are produced by people and institutions that do not simultaneously estimate the costs associated with climate change, either damages or costs of adapting; the estimates do not optimize the combined costs of abatement and climate change. A "not unreasonable" target for reduction might be delaying a doubling by, say, four decades. One decade might be too trivial, a century too ambitious, and four decades an objective in which most audiences would be interested. But nobody who makes such an estimate wishes to be interpreted as proposing that when all the uncertainties about climate changes and their impacts have been resolved, if they ever are resolved, the optimum reduction in emissions will be found to retard doubling by 40 years, or any other specified period of time.

All I can do to summarize a multitude of estimates is to specify an order of magnitude that many economists and the Congressional Budget Office would not consider outrageous. That is the figure I mentioned earlier, possibly 2 percent of GNP for the developed countries and a similar, but even much more uncertain, percentage of GNP for the developing world. The uncertainty for the developing world is partly due to the estimates being mainly derived from the American economy.⁴

Two characteristics of these estimates need to be emphasized. One is that they tend to assume optimal technological adjustment, as in response to a carbon tax. To the extent that carbon emissions are controlled by direct regulatory measures, there may be the usual expected inefficiencies, and I leave the reader to make his own adjustment.

⁴Several critiques and surveys of different abatement-cost estimates are available (see Congressional Budget Office, 1990; Joel Darmstadter, 1991; William D. Nordhaus, 1991b; Energy Modeling Forum, 1992).

The second is that, since the early years of the energy crisis in the 1970's, there have been enthusiastic portrayals of currently available technologies, ranging from light bulbs to electric motors, double-glazed windows and improved internal-combustion engines, that for some reason have not been successfully marketed. The interest continues, and the recent National Academy of Sciences study gave sympathetic attention, but no analysis, to a number of proposals for residential, commercial, industrial, and transportation energy management and for improved electricity production and fuel supply and concluded that, including reductions in CFC's, "The United States could reduce or offset its greenhouse gas emissions by between 10 and 40 percent of 1990 levels at low cost or at some net saving, if the proper policies are implemented" (1991 p. 73).

All of these ideas are completely orthogonal to the econometric estimates. The Academy panel that produced the report was unable to offer an explanation for why these low-cost or negative-cost technologies have not caught on. Its quantitative assessment, including an allowance for elimination of CFC's, ranged from as little as 10 percent to as much as 40 percent of current U.S. emissions; CFC's aside, their range of possibility is from zero to about 30 percent. Whatever the correct figure, this is probably a once-and-for-all backlog of accumulated technologies, which once exploited may be permanent but not progressive. But the strong suggestion is that there is a lot to be accomplished in the next two or three decades.

VIII

With these qualifications, let us look at that 2 percent of GNP as a permanent reduction over the coming century. I consider it altogether improbable that the developing world, at least for the next several decades, will incur any significant sacrifice in the interest of reduced carbon (nor would I advise developing countries to do so). Anything done to reduce emissions in China, India, or Nigeria will be at the expense of the richer countries.

Financing energy conservation, energy efficiency, and switching from high-carbon to lower-carbon or noncarbon fuels in Asia and Africa would not only be a major economic enterprise but a complex effort in international diplomacy and politics. If successful, it would increase the costs to the developed world by at least another percent or two on top of the 2 percent I mentioned. It is furthermore not easy to hide the transfer of resources on the order of a couple of hundred billion dollars, dollars "budgeted" somehow or other, compared with hiding some of the costs due to regulation, such as automobile fuel-efficiency standards in the United States. The kind of thing we are talking about is inducing the Chinese, through our somehow offsetting their cost, to forgo a massive electrification based on coal and the cheapest coal-combustion technology. Without engaging in blackmail, the Chinese can assert that it is not in their interest to do that at their own expense, even if they are the keystone of a "social contract" and no other nation will do anything unless the Chinese fully participate.

I shall sketch what I can imagine as a major attack on the greenhouse problem. And I should be explicit about what I cannot imagine. For reasons that I would be delighted to elaborate but for which I cannot take space here, a universal uniform carbon tax is not a solution that I can imagine. My reason is simple. A carbon tax sufficient to make a big dent in the greenhouse problem would have to be roughly equivalent at least to a dollar per gallon on motor fuel, and for the United States alone such a tax on coal, petroleum, and natural gas would currently yield close to half a trillion dollars per year in revenue. No greenhouse taxing agency is going to collect a trillion dollars per year in revenue; and no treaty requiring the United States to levy internal carbon taxation at that level, keeping the proceeds, would be ratified by the Senate. Reduce the tax by an order of magnitude and it becomes imaginable, but then it becomes trivial as greenhouse policy.⁵

⁵A careful treatment of the universal carbon tax is provided by James M. Poterba (1991).

Tradable permits have been proposed as an alternative to the tax. There are two main possibilities: (i) estimating "reasonable" emissions country by country and establishing commensurate quotas or (ii) distributing tradable rights in accordance with some "equitable" criterion, such as equal emissions per capita (a possibility that has actually been discussed). Depending on how restrictive the aggregate of such tradable emission rights might be, the latter is tantamount to distributing trillions of dollars in discounted value and making, for a country like Nigeria, the outcome of its population census the country's major economic policy. If, instead, quotas are negotiated to correspond to every country's currently "reasonable" emissions level, they will surely be renegotiated every 5 or 10 years, and selling an emissions right will be perceived as evidence that a quota was initially too generous. It is unlikely that governments will engage in trades that acknowledge excessive initial quotas.

I do not foresee negotiated national quotas subject to serious enforcement, especially enforcement through financial penalties. I think any international regime for carbon abatement can seriously include only the developed countries, and I exclude from this category the countries that we used to call the Eastern Bloc. I can easily imagine institutional arrangements that are universalist, some kind of "framework agreement" to which every country subscribes, with specific commitments to be negotiated later. But I expect serious commitments to be undertaken only by the countries that can afford to, and I am undecided whether an institutional pretense of a universalist system has advantages or, instead, the developed world should proceed independently and unencumbered with the need for a universalist facade.

The model that I find most helpful in conceptualizing a greenhouse regime among the richer countries is the negotiations among the countries of Western Europe for distributing Marshall Plan dollars among themselves and the negotiations, beginning in 1951, on "burden sharing" in NATO. There was never a formula for distributing

Marshall Plan dollars; there was never an explicit criterion, such as equalizing living standards, equalizing growth rates, maximizing aggregate output or growth, or establishing a floor under levels of living. Baseline dollar-balance-of-payments deficits were a point of departure, but the negotiations took into account investment needs, traditional consumption levels, war-induced capital needs, opportunities for import substitution and export promotion, and opportunities to substitute intra-European trade for trade with hard-currency countries.

The United States insisted that the recipients argue out and agree on shares. In the end, they did not quite make it, the United States having to make the final allocation. But all the submission of data and open argument led, if not to consensus, to a reasonable appreciation of each nation's needs. The negotiations were professional; they were assisted by a proficient secretariat. The resources involved for most recipient countries were immensely important. Good relations were observed throughout; and proficiency in debate, acceptance of criteria, and negotiating etiquette steadily improved.

That is the only model I find plausible, and I believe distribution of Marshall Plan and defense-support funds to Europe is the only model of multilateral negotiation involving resources commensurate with the cost of greenhouse abatement. (In the first year, Marshall Plan funds were about 1.5 percent of U.S. GNP and—adjusting for overvalued currencies—probably 5 percent of OEEC GNP).

What that model suggests is that the main participating countries in a greenhouse-abatement regime would submit for each other's scrutiny and cross-examination plans for reducing carbon emissions. The plans would be accompanied by estimates of emissions or emissions reduction from some projected level, but any commitments undertaken would be to the policies, not the emissions. And not all of the plans would necessarily be commitments.

The United States, for instance, could present a plan for the introduction of a new generation of nuclear power reactors beginning sometime in the next century, but it is

difficult to see how the federal government can commit itself to what reactors public utilities will be purchasing 20 years from now. The United States can have a plan to mandate fuel-efficiency standards for automobiles, but it takes 10 years for the standards to work their way into the automobile fleet, and there is no accounting procedure that will estimate the effect on motor-fuel consumption of any level of average fuel efficiency a decade from now.

The current popular expectation is that participation in any greenhouse regime will take the form of commitments to specified percentage reductions of emissions below those of some specified year, like 1990 or 2000. I cannot help believing that adoption of such a commitment is an indication of insincerity. A serious proposal would specify policies, like taxes, regulations, and subsidies and would specify programs (like research and development), accompanied by very uncertain estimates of their likely effect on emissions. In an international public forum, governments could be held somewhat accountable for the policies they had or had not put into effect, but probably not for the emissions levels achieved.

Such a modest beginning will require finding a way to sublimate the current international enthusiasm for a new universalist greenhouse regime into institutional arrangements that are helpful but noncommittal when the U.N. Conference on Environment and Development convenes next June. This will require an understanding among the developed countries that it is initially up to them to find a way to mobilize their populations in support of national greenhouse policies.

IX

A major commitment to financing emissions abatement in the developing world is surely too far away to need specific plans now. A developing-world carbon-abatement effort would, in principle, be altogether different from foreign aid as we have known it since World War II. In principle it would all be directed, from whatever sources and through whatever channels, to protecting

that same global common. There would be, for the first time, a single criterion: economizing carbon. In the abstract, aid recipients in the war on greenhouse gases would not compete; they would not make India–Pakistan comparisons, or Arab–Israel, or Poland–Czechoslovakia. All would in principle benefit equally from maximum carbon conservation, wherever it could be achieved. Trees may grow more rapidly, in carbon content, in Madras or Szechuan or Borneo or Alaska or South Carolina, but if someone were willing to finance the growth of a tree to absorb carbon dioxide, the citizens of those states should not have the slightest care where the tree were to be planted; they all benefit solely from the carbon fixed in the tree and benefit more, the faster the tree grows, no matter where it grows.

It wouldn't work that way, of course. Somebody gets the shade, or leases land for the tree; and if it's not a tree but a nuclear power plant to supplant coal, there are local impacts that make huge differences, and negotiations over sharing the cost differential between the coal and the nuclear plants. But it is worth noticing that if there were a "pure" carbon-abatement or carbon-absorbing technology, one that accomplished nothing else, there should be no dispute about locating it wherever it would be most effective. That is new in foreign aid and foreign investment.

If the developed countries ever manage to act together toward the developing countries, their bargaining position is probably enhanced by the fact that cleaner fuels and more efficient fuel technologies bring a number of benefits other than reduced carbon, and recipients of greenhouse aid will be actively interested parties, not merely neutral agents attending to the global atmosphere. At the same time, large nations like India and China will be aware of the extortionate power that resides in ambitious coal-development projects.

On a greatly reduced scale, there may be something constructive to do more immediately. There is a huge difference between transferring "technology" and transferring capital goods that embody technology or, going further, financing entire investments

(local construction, etc.) in which the technology is embedded. The difference in cost is at least an order of magnitude. While the developed countries are feeling their way into some common attack on their own carbon emissions, a tangible expression of their interest and an effective first step would be to establish a permanent means of funding technical aid and technology transfer for developing countries, as well as research, development, and demonstration in carbon-saving technologies suitable to those countries. Eventually the rural Chinese household may cook more efficiently with nuclear-powered electricity, but for another generation or two what is important is less carbon-wasteful ways of cooking and heating.

Maybe there is a role here for the carbon tax. Western Europe, North America, and Japan will be burning 3 or 4 billion tons of carbon per year for the next decade. Taxing themselves, that is, contributing in proportion to the carbon they consume, at one, two, or three dollars per ton, they could contribute to a fund that might begin at \$3 billion per year and grow to \$10 billion. The carbon tax is a little arbitrary here, and a U.S. administration may be wary about a precedent that carries over when the tax rises an order of magnitude, but compared with alternative criteria for sharing costs it might not even be a bad precedent.

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