

Climate and Economic Development *Climates Past and Climate Change Future*

William D. Nordhaus

Economists and development practitioners have a long agenda of concerns, ranging from obsolete capital to inadequate education. Many fear that we are adding to this list by damaging the natural environment through a multitude of interventions, such as the release of greenhouse gases. This paper places the issue of climate change in the context of broader discussions on economic development. It reviews alternative approaches to the role of climate, contrasting an older theory of climatic determinism with modern adaptive approaches. It then briefly reviews concerns about greenhouse warming and surveys current research on the impact of global warming on economic activity. The paper emphasizes the critical need for effective policies, perhaps using carbon taxes, if we are to attain global environmental objectives without placing excessive burdens on economic growth.

Practitioners of economic development have a long agenda of concerns, including the inadequacy of public and private capital, poor training and education of workers, and counterproductive attitudes, ideologies, and practices. It is feared that we are adding another list of potential problems to this already heavy burden by damaging the natural environment through a multitude of interventions, such as injecting greenhouse gases or ozone-depleting chemicals into the atmosphere, engineering massive changes in land use, depleting species in their natural habitats (even as transgenic varieties are created in the laboratory), and accumulating nuclear weapons that could destroy human civilization. As natural or social scientists we need to understand the human sources

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of these global changes, their potential for damaging environmental and economic systems, and the most efficient ways of alleviating their undesirable consequences. Just as once the interests of future generations dictated the conservative management of grazing and water resources, so must we today learn to use and protect our geophysical and biological resources. This task of understanding and controlling interventions can be called "managing the global commons."

This paper examines interventions for mitigating damage to the environment from greenhouse warming—a rise in temperature caused by emissions of greenhouse gases. Many scientific bodies, along with a growing chorus of environmental groups and governments, are calling for severe curbs on these emissions on the grounds that the interests of future generations are at stake. The response, in the form of a treaty to monitor national trends and policies on climate change, emerged from the 1992 "Earth Summit"—the United Nations Conference on Environment and Development.

Natural scientists have pondered the question of greenhouse warming for a century. Only recently have economists begun to study the effects of climate change, the costs of slowing these changes, and alternative approaches for implementing policies. Most of the research has focused on the United States and Europe. Few attempts have been made to explore global warming in the developing world, even though many scientists fear that the most adverse effects are likely to occur in poorer countries.

This paper places the issue of climate change in the context of the debate on economic development. Given the paucity of data on which to base an economic analysis, the approach must be impressionistic at this stage.

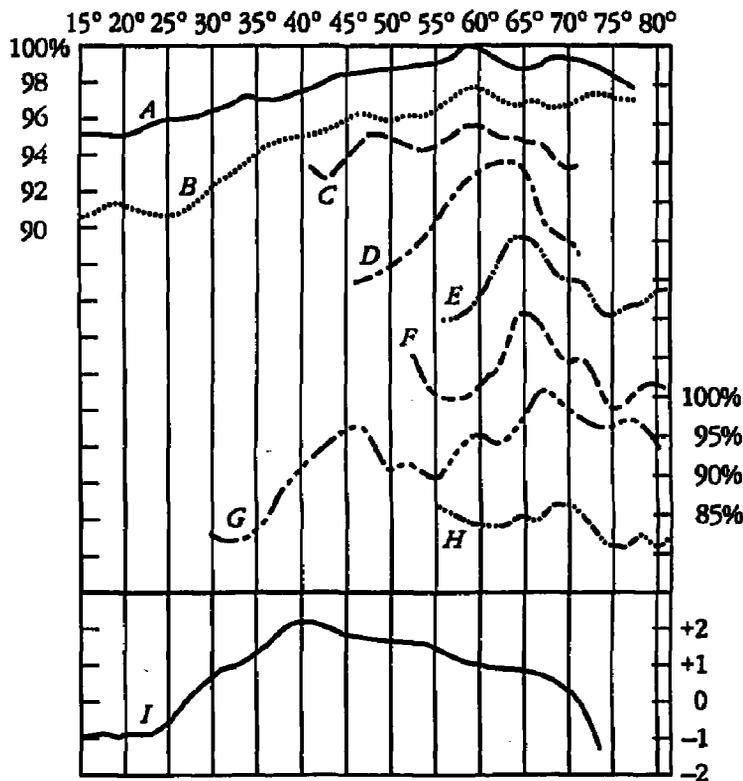
The Ghosts of Climates Past

From the age of Aristotle until early in this century, most philosophers and scientists who reflected on the progress of nations assumed that climate was among the chief determinants of the differences among nations. This view was summarized in 1915 by the eminent Yale geographer Ellsworth Huntington, who wrote, "The climate of many countries seems to be one of the great reasons why idleness, dishonesty, immorality, stupidity, and weakness of will prevail."

About the middle of this century, climate virtually disappeared from the economic development literature, eclipsed by such "modern" factors as investment, trade policies, and education. In the past few years, however, with the threat of global warming, climate has reemerged as the centerpiece of international environmental issues. Whereas Huntington reported on the influence on health and economic activity of "temperature, humidity, wind movements, storminess, variability, and sunlight," today geographers and environmentalists worry about the effects of droughts, a rise in the sea level, species depletion, and loss of ecosystem diversity.

Huntington's approach is illustrated by figure 1, which looks at the effect of outside temperature on physical and mental performance. The top eight curves

Figure 1. Human Activity and Mean Temperature



- A. 300 Men in Two Connecticut Factories, 1910-13.
- B. 196 Girls in One Connecticut Factory, 1911-13.
- - - C. One Man (P) in Denmark, June-December, 1906.
- · - · - D. One Man (L) in Denmark, June-December, 1906.
- · — E. 380 Cigar-makers in Factory B at Tampa, Fla., 1913.
- - - F. 400 Cigar-makers in Factory A at Tampa, Fla., 1913.
- G. 3 Children Typewriting in New York 1905-6.
- · - · - H. 380 Cigar-makers in Factory B at Tampa, Fla., 1912.
- I. 1560 Students in Mathematics and English at West Point and Annapolis, 1909-1913.

Note: All the curves except G and I are drawn on the same scale. The maximum in every case is reckoned as 100.

Source: Reproduced from Huntington 1915, p. 124.

show variations in wages, where wages reflect workers' productivity. The bottom curve shows performance in mathematics and English by students at the U.S. military academies. From these data Huntington concluded that maximum productivity for physical effort occurs at a temperature between 59°F and 65°F, while "people do their best mental work when the [outside] temperature ranges from freezing to about 50°" (p. 128).

Many other findings spring from Huntington's imaginative interpretation of his and others' data. One entertaining hypothesis concerned the role of sunlight. In a tract entitled *The Effect of Tropical Light on White Men*, a U.S. Army surgeon, C. W. Woodruff, speculated that the backwardness of tropical countries was a result of excessive sunlight. Woodruff's theory held that sunlight at the blue end of the spectrum would fall on the human body and overstimulate cell growth—as in an overripe fruit. Huntington examined data on factory workers and found no or only slight effects from light, but he did uncover other patterns.

Taking the year as a whole, uniformity of temperature causes low energy; a slight rise is beneficial, but a further rise is of no particular value; the beginning of a fall of temperature is harmful, but when the fall becomes a little larger it is much more stimulating than a rise; when it becomes extreme, however, its beneficial qualities begin to decline. (Huntington 1915)

Having reviewed these results, Huntington turned to his central thesis, the climatic hypothesis of civilization. Three important conclusions emerge here and in his other works. The first hypothesis links climate change with the rise of important civilizations, using Greece as a principal example. I quote the entire summary to give a flavor of the reasoning.

To sum up the whole hypothesis of the relation of climate to civilization, here are the factors as I see them at present. Most parts of the world are so well populated that any adverse economic change tends to cause distress, disease, and a high death rate; migration ensues among the more energetic and adventurous people. Perhaps the commonest causes of economic distress are variations in weather or climate which lead to bad crops or to a dearth of grass and water for animals. Such economic distress almost inevitably leads to political disturbances and this again is a potent cause of migrations. The people who migrate perforce expose themselves to hardships and their numbers diminish until only a selected group of unusually high quality remains. Such people, either as warlike invaders or in small bands, enter a new country. They may find it well populated and merely impose themselves as a new ruling class, as seems to have happened several times in India, or they may find it depleted of people as in Attica. When the period of climatic stress is ended and the climate improves, the dominant newcomers not only possess an unusually strong inheritance, but are stimulated by unusually good economic conditions and by improved conditions of health and energy. Moreover since the population is apt to remain below the saturation point so long as the climate improves, the standards of living tend to rise and to become relatively high. Thus many people are freed from the mere necessity of making a living and have the opportunity to devote themselves to the development of new

ideas in literature, art, science, politics, and other lines of progress.
(Huntington 1915)

We see here the long shadow of Malthus interacting with crude Darwinism and Huntington's dynamic-climate theory.

The second hypothesis makes the case for a kind of climatic fatalism. Huntington argues that people in the American South have "less energy, less vitality, less education, and fewer men who rise to eminence than in the North, not because southerners are in any way innately inferior to northerners, but apparently because of the adverse climate." About other countries he asks: "What shall we say of Russia, weighted down with benumbing cold and comparative monotony or with changes so extreme that they are harmful?" and "What of China under a much heavier handicap of monotony; or of tropical lands burdened most heavily of all?"

The third feature lifts his work out of the ordinary run of climatic (or other) mechanistic theories and provides a link to modern economic views of climate change. How is it that Hong Kong or Japan—far down Huntington's scale of climatic potential—could break free of their climatic chains and prosper?

Huntington observed that "in the past great inventions have helped chiefly in enabling man to overcome low temperature; in the future, perhaps, they will help him in equal measure to overcome high temperature, dryness, and monotony." He speculates, with uncanny foresight for a book written well before Freon was formulated, that technology has the potential to improve the situation in tropical countries.

In the warmer parts of the earth [alleviating hot temperatures requires] cooling the interiors of houses. Today this is done on a small scale by shutting out the sun and sprinkling water to cause evaporation. There is no reason why the same result should not be produced on a large scale. We already know how to cool houses as well as to heat them. We do it in ice-plants. A thousand years ago men would have laughed at the idea that hundreds of rooms would some day be heated by a single fire, yet we see it in every office building or hotel. In equatorial regions there is as much reason for equipping the houses with coolers as there is in temperate regions for equipping them with heaters. (Huntington 1915)

He concludes loftily that "if we can conquer climate, the whole world will become stronger and nobler."

Huntington's work, along with a small library produced by other scholars, is a healthy reminder of how our fundamental models of human activity are prisoners of conscious or unconscious models of social systems. In Huntington's case the influence of Malthus and Darwin constrained his theory of climate and civilization. It is surprising that he did not ask whether the effects of climate were negligible in the light of the economic pace of human invention he described. The difference in performance between the "optimal" 60°F tempera-

ture for New York City and an 80°F average temperature in a tropical region hardly exceeds 2 percent. Yet real wages and productivity in his day were routinely growing at that rate every year. The real puzzle for a climatic determinist like Huntington was why productivity in the tropics was so much lower than was predicted by the wage-temperature curves. Had Huntington asked that question, he might have become a development economist!

The Impact of Climates Present

Modern views of economic development give short shrift to climate as the basis for differences in the wealth of nations.¹ A review of a handful of textbooks on economic development shows that the discussion of climate is confined to only a few lines.² The modern view of economic growth presents development as a vehicle driven by the four wheels of capital, labor, resources, and technology, and it is a stretch of interpretation to equate resources with climate. The recent wave of studies of international differences in productivity has never included climate as a determining variable. Modern trade theorists have had difficulty finding empirical evidence to confirm Heckscher-Ohlin trade theories that international trade is based on a region's resource base (which would include climate along with other factor endowments).

How can we rationalize modern attitudes toward climate? One possible explanation is that there seems little point in studying the influence of so exogenous a variable. A more serious possibility is that societies can adapt to whatever climate is dealt by nature. In this section I explore this view and then examine some economic and geophysical data to determine whether the evidence supports the earlier climatic determinism or an alternative, which I will call the adaptive theory of climatic impact.

The adaptive theory holds that in the very long run humans beings are essentially nomadic toolmakers. They can usually invent products or processes to offset the disadvantages of climate or can by trade turn apparent disadvantage to economic profit. At the extremes of cold, Sherpas make a relatively good living leading people up Mt. Everest, while deserts, free of ice and snow, are increasingly attractive as retirement sites. And a region that is so barren as to attract no conventional economic activity will probably become attractive as a wilderness retreat.

In the short run, of course, life can be full of surprises and dreadful climatic shocks. *Homo adaptus* will still be rendered homeless if hurricanes destroy flimsy structures, if storm surges break across land that is not meant for risk-free habitation, if farmers cultivate drought-prone land, or if civil wars destroy the land or dampen entrepreneurial impulses. To say that human beings are adaptive says nothing about whether the adapted standards of living are high or low, whether nations are at war or peace, whether the climatic shock is the straw that breaks the camel's back, or whether policies should be designed to prevent the laying of that last straw (through large investments to slow climate change) or to

lighten the load from other burdens so that occasional climate shocks are nuisances rather than catastrophes.

Figure 2 illustrates the adaptive view of climatic effects. The horizontal axis represents a synoptic climate variable such as average temperature; the region's productivity is on the vertical axis. The horizontal line LR represents the long-run productivity of a region and suggests that productivity is independent of climate. In the short run, however, productivity will be maximized at the "design climate." I therefore represent SR_0 as the productivity curve that corresponds to capital, management, infrastructure, and localized technologies that are designed for climate T_0 . If climate were to change to T_1 , cool-weather crops would wilt, ski areas would fail, and other signs of an ill-adapted technology would emerge, with the equilibrium moving from A to B and productivity falling from P^* to P_1 . Over time, however, the economy would adapt, as tropical fruits replaced temperate grains and campers replaced skiers. Once all the adaptations had taken place, productivity would rise to point C , with a productivity equal to the initial level and with a new short-run productivity curve of SR_1 .

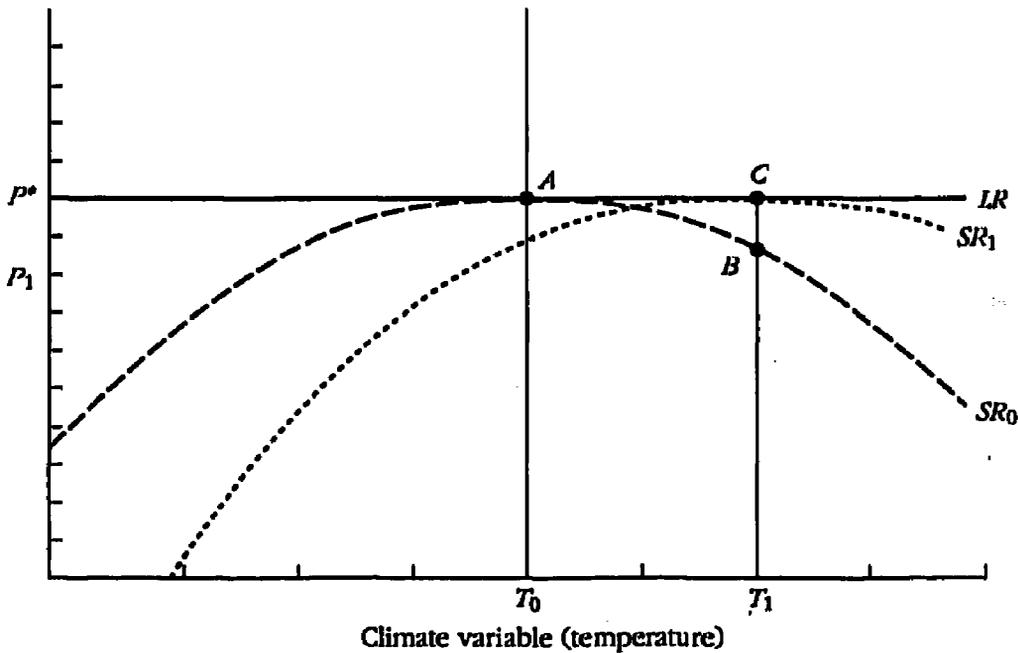
Figure 2 makes two other important points about adaptive systems. Not surprisingly, the first is that large shocks have a stronger short-term impact than do small shocks. The second, quite surprising, implication is that, to a first order of approximation, small shocks have no impact. To be more precise, a small climate shock in the short run, before any adaptation has taken place, has the same impact as a long-run shock, or a shock that occurs after adaptation has taken place. In terms of figure 2, a small shock will move along the short-run productivity curve, which is tangent to the long-run productivity curve at the initial point.

Many objections can be raised to the adaptive view in figure 2. One valid objection is simply that some aspects of social or natural systems either cannot adapt or adapt so slowly that significant damage cannot be avoided. Forest ecosystems, coral reefs, cultural treasures such as Venice, wildlife refuges such as Yellowstone—for these, the possibilities of adaptation seem dubious, and the short-run curve might well last for two centuries rather than two years. A second class of objection is that the long-run curve would not be horizontal but would show marked losses as climate changes. Such a case might arise if climate change involved global glaciation, if there were a shift in ocean currents that changed the climate of the North Atlantic communities into that of Alaska, or if midcontinental warming and drying destroyed the globe's grain belts.

Using modern income concepts, I examine the relationship between certain geophysical variables and different economic measures. Two elementary variables, latitude and average temperature, represent climate. Clearly, these variables are too aggregated for large countries such as the United States, which spans 52 degrees of latitude from Hawaii to Barrow, Alaska. But for smaller countries such as Belgium or Gabon, the climatic variables do not mask great diversity. Figures 3 and 4 show the relationship between the geophysical vari-

Figure 2. Productivity and Climate in an Adaptive Economy

Productivity

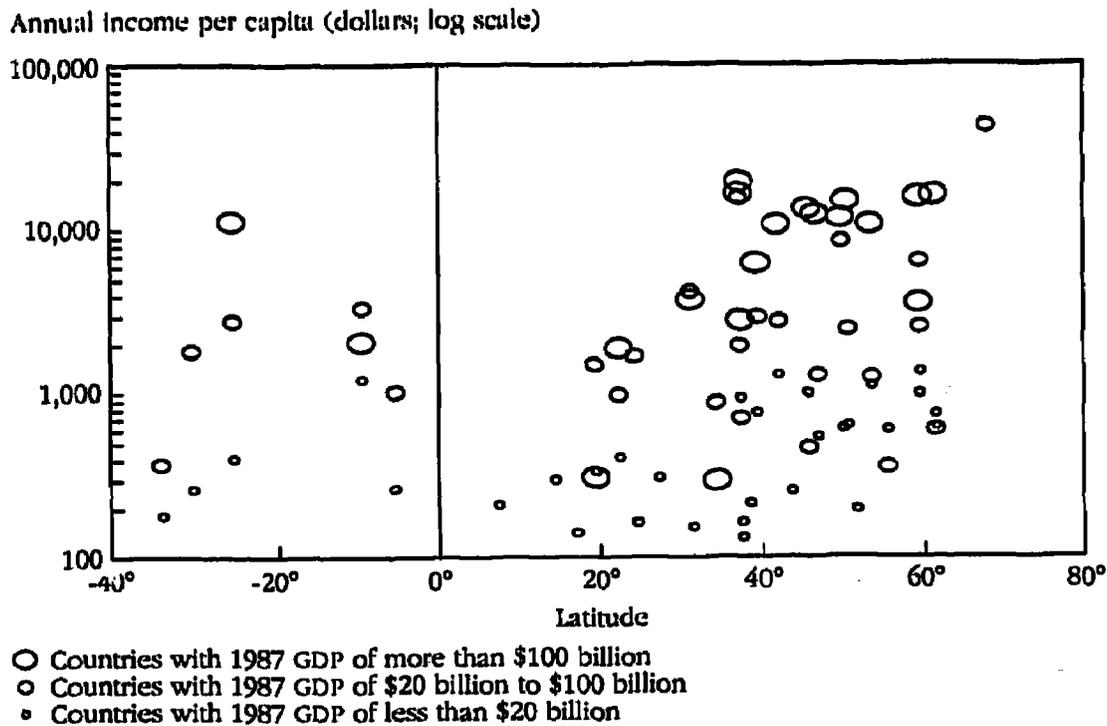


Note: LR, long-run productivity; SR, short-run productivity.

ables and per capita incomes. Figure 3 indicates that the zone from 10° south latitude to 20° north latitude is an economic desert in which no country has achieved high levels of income per capita. In the latitudes toward the poles from 35° north or 25° south, however, there is virtually no relationship between latitude and economic performance. Figure 4 shows the relationship between income per capita and temperature for a smaller sample of countries. In most of the range, from a mean temperature of 40°F to about 65°F, there is no relationship between mean temperature and income per capita. Above an average temperature of 65°F only a handful of countries show a relationship, but no country in this sample with a mean temperature of more than 65°F has risen above the \$2,000 per capita income level.

The measure of income per capita is somewhat defective in that over a scale of centuries human migrations will tend to equalize incomes in different regions (although the tendency is clearly quite weak in light of current findings on the lack of convergence among countries). In 1980 Alaska had the highest income per capita in the United States, and we might therefore mistakenly conclude that Alaska has a very fertile climate. A better measure of the economic clemency of a climate would probably be the “Ricardian rent” that land in any area yields.

Figure 3. Latitude and Income Per Capita



Note: A sample of seventy-seven countries was used. Latitude is that of the geographic center of the country. Income is based on 1987 GDP per capita, using the exchange rates corrected for purchasing power parity that were developed by the International Income Comparison Project. These adjusted data reflect more realistic estimates of income per capita in the formerly centrally planned economies.

Source: Income and area data from World Bank 1992, adjusted by author.

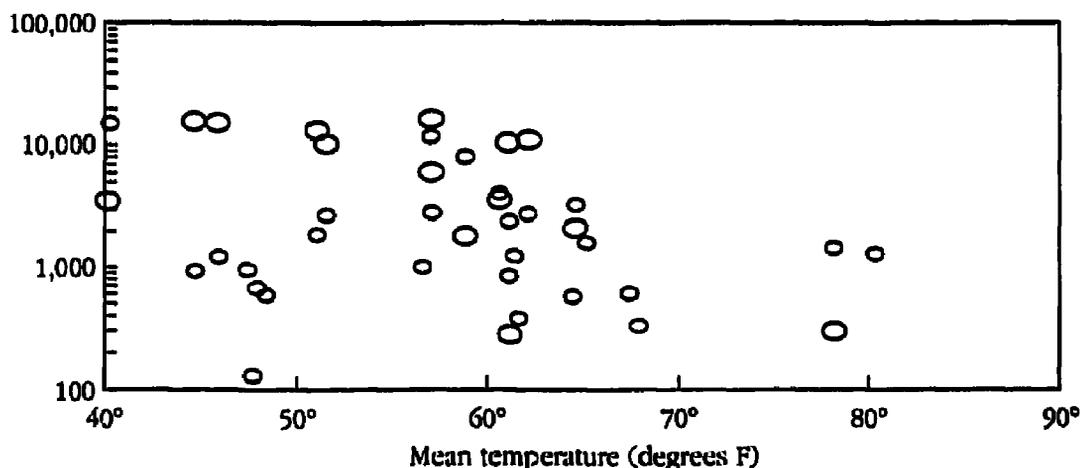
Failing that, we could examine income measured as a country's GNP per unit area.

Figures 5 and 6 show the results of this calculation. Figure 5 shows the same latitudinal result as figure 3—an economic desert in the lowest latitudes. But the interesting new feature here is that the economic return per unit area peaks in the middle latitudes—say between 40° and 50° north latitude and about 30° south latitude—and then declines again at the highest latitudes. This reflects the sensible result that the high incomes in the highest latitudes (Alaska, northern Canada, and Siberia) go to only a few people.

In figure 6 there seems to be more of a standoff between the variables. Income per unit area is highest in temperature ranges that are more moderate, and a modest hump-shaped relationship is evident. But no clear threshold appears in these data.

Figure 4. Temperature and Income Per Capita

Annual income per capita (dollars; log scale)



- Countries with 1987 GDP of more than \$100 billion
- Countries with 1987 GDP of \$20 billion to \$100 billion
- Countries with 1987 GDP of less than \$20 billion

Note: A sample of forty countries was used. Temperature is the average of the July and January maxima and minima. For income per capita, see note to figure 3.

Source: Income and area data from World Bank 1992, adjusted by author.

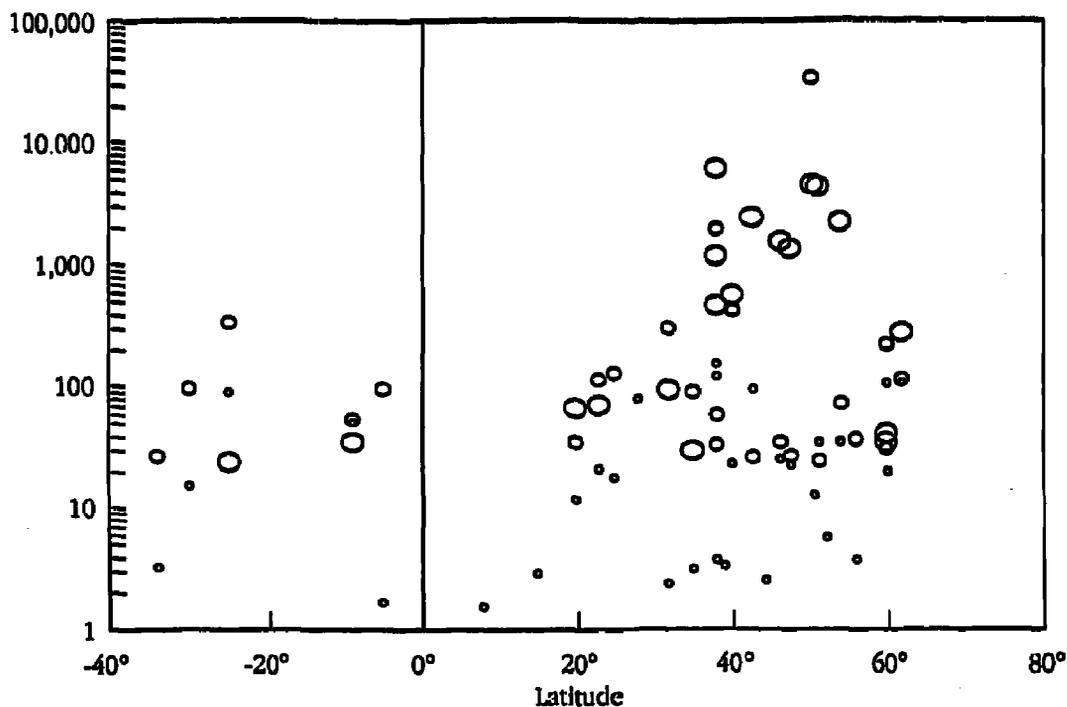
A final word should be added to put these geophysical variables in a larger context. Climate may have an effect on income, but the effect is swamped by other variables. Looking at figure 5, we see that incomes per square kilometer vary from a low of about \$31 in China to a high of about \$36,000 in Hong Kong, and from \$37 in Indonesia to \$6,200 in Japan. Latitude explains less than 1 percent of the variance in income per capita or per area. We should surely look to factors other than climate to explain most differences in the wealth or poverty of nations.

The Threat of Climates Future

Climate has reemerged on center stage in the past few years as scientists have become increasingly concerned about the greenhouse effect—the process by which radiative “greenhouse” gases such as carbon dioxide (CO₂) selectively absorb radiation at different points of the spectrum and thereby warm the surface of the earth. The major greenhouse gases (GHG) are carbon dioxide (emitted primarily from the combustion of fossil fuels), methane, and chloro-fluorocarbons (CFCs). GHGs are transparent to incoming solar radiation but absorb significant amounts of outgoing radiation. There is no debate about the

Figure 5. Latitude and Income Per Unit Area

Income per square kilometer (dollars; log scale)



- Countries with 1987 GDP of more than \$100 billion
- Countries with 1987 GDP of \$20 billion to \$100 billion
- Countries with 1987 GDP of less than \$20 billion

Note: A sample of seventy-seven countries was used. For latitude and income, see the note to figure 3.

Source: Income and area data from World Bank 1992, adjusted by author.

positive importance of the greenhouse effect, without which the earth's climate would resemble the moon's.³ But the trend toward greenhouse warming is a pressing concern.

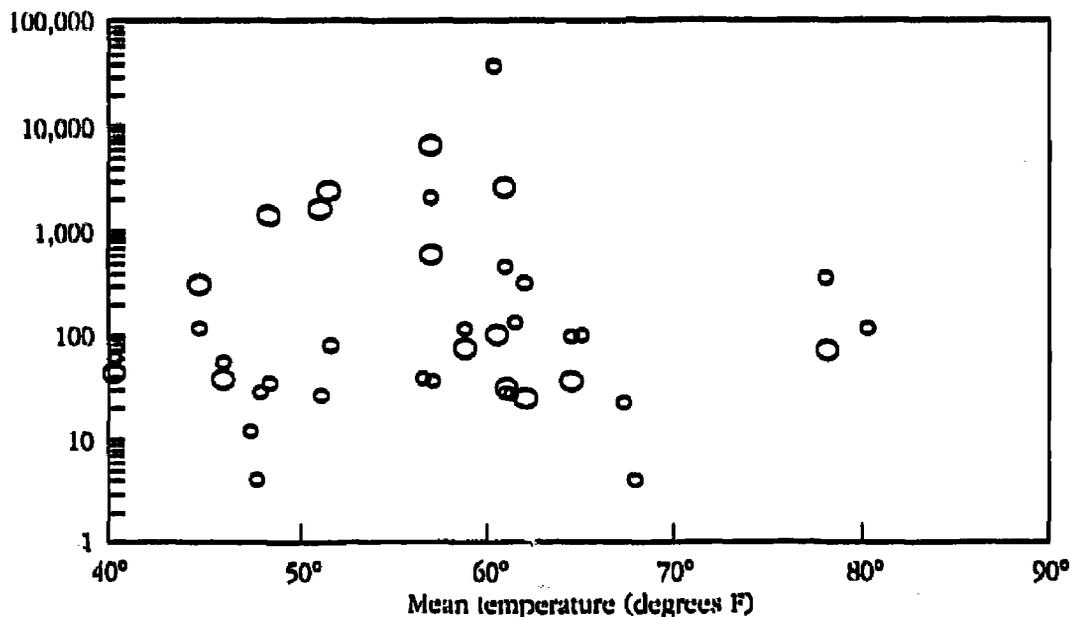
The Greenhouse Effect

Concern about the greenhouse effect arises because human activities are currently raising atmospheric concentrations of greenhouse gases. Using the standard metric measure of the "CO₂ equivalent" of GHGs, we find that atmospheric concentrations have risen by more than half the preindustrial level of CO₂.

Although the historical record is well established, there is great uncertainty about the potential for future climate change. On the basis of climate models, scientists project that a doubling of the atmospheric concentrations of CO₂ will in equilibrium lead to a 1° to 5°C warming of the earth's surface; other pro-

Figure 6. Temperature and Income Per Unit Area

Income per square kilometer (dollars; log scale)



- Countries with 1987 GDP of more than \$100 billion
- Countries with 1987 GDP of \$20 billion to \$100 billion
- Countries with 1987 GDP of less than \$20 billion

Note: A sample of forty countries was used. For temperature, see the note to figure 4. For income per capita, see the note to figure 3.

Source: Income and area data from World Bank 1992, adjusted by author.

jected effects include an increase in precipitation and evaporation, a small rise in sea level over the next century, and the potential for hotter and drier weather in such midcontinental regions as the U.S. Midwest.

To translate these equilibrium results into a projection of future climate change requires a scenario for predicting emissions and concentrations. Using rudimentary economic modeling, the Intergovernmental Panel on Climate Change (IPCC), an international panel of distinguished scientists, projected that "business as usual" would produce a 3° to 6°C warming by 2100. Economic models tend to show lower emissions and temperature trends than the extrapolative approaches often used. Virtually all the projections are worrisome, however, because climate appears to be heading out of the historical range of temperatures witnessed during the entire span of human civilization.

Climate models resemble large macroeconomic models in their ability to answer any question that modelers care to ask; it is not clear that their reliability for forecasting climate change is any better than that of their economic counterparts. Climate models are currently unable to replicate actual climates reliably,

and many climate modelers do not expect to be able to forecast regional climates accurately in the foreseeable future. Some scientists believe that there may be "regime changes" in which the climate flips from one locally stable system to another, say, because of changes in ocean circulation. Elaborating bigger and better models will provide full employment for climatologists well into the next century.

What are the likely effects of projected changes in climate? It is important to recognize that the critical variable in most analyses—average global temperature—is relatively unimportant. Variables that accompany or are the result of temperature changes—precipitation, water levels, extremes of droughts or freezes, and thresholds such as the freezing point or the level of water contained by dikes and levees—are what will drive the socioeconomic consequences. Mean temperature is chosen because it is a useful index of climate change that is highly correlated with or determines the more important variables.

Effects of Changes in Climate in High-Income Regions

What do empirical studies say about the economic impact of climate change? Because such studies are in their infancy and research on low-income regions is virtually nonexistent, I have concentrated in this paper on high-income regions.

Climate change is likely to have different effects on different sectors. (A 1989 study by the U.S. Environmental Protection Agency emphasizes the potential costs of climate change; a more balanced approach is contained in National Academy of Sciences 1992.) In general, those sectors that are heavily dependent on naturally occurring rainfall, runoff, or temperatures will be most sensitive to climate change. In reality, however, most economic activity in high-income countries has little direct interaction with climate. Cardiovascular surgery and microprocessor fabrication, for example, are unlikely to be affected by climate change, and the same is true of mining, manufacturing, communications, and most services—sectors that comprise 80 to 85 percent of gross domestic product (GDP) in high-income countries.

Table 1 shows the results of three studies by Nordhaus (1991), Cline (1992), and Fankhauser (1992) that estimate the effect on the United States of a doubling of CO₂, estimated to lead to a temperature rise of 2.5° to 3°C. Cline has performed the most detailed economic analysis, but his results are often fragile and may overestimate climatic impacts. For example, he assumes that storms will become more severe, whereas both the IPCC and the National Academy of Sciences studies conclude that global warming has an ambiguous effect on storm intensity. On another point, species loss, Cline selects as the basis for valuation a very costly environmental decision, that of the spotted owl. Finally, Cline's estimate for agriculture is much higher than that in recent studies by Reilly and Hohmann (1993) and by Mendelsohn, Nordhaus, and Shaw (1993). Cline's estimates (1.1 percent of GNP for a 2.5°C increase in warming) are marginally above those in the

Nordhaus survey (1 percent of GNP for a 3°C increase in warming). The results of the Fankhauser study, which extends the analysis to the countries of the Organization for Economic Cooperation and Development (OECD) and to the world, are close to the findings in other studies: a 3°C rise in temperature yields a 1.3 percent of GNP impact for the United States and a 1.5 percent global impact.

Two other approaches are shown in table 1. First the study by Reilly and Hohmann (1993) embeds the crop-yield models used to develop the impact estimates for agriculture in a model of international trade. The authors find that trade tends to reduce the impacts by one to two orders of magnitude as supply and demand reactions buffer production shocks. The estimated impact of a substantial (30 percent) yield shock, buffered by the adaptive response in markets, produces a negligible impact on U.S. and global incomes.⁴ This careful study is a good example of the tendency to exaggerate losses while ignoring gains and adaptation.

A second study (Nordhaus forthcoming), more qualitative in nature, reports the results of a survey of experts on the economic impacts of climate change. For a 3°C warming in 2090, the "trimmed mean" of the responses estimates damages of 2.9 percent of world output; the median is 1.8 percent of world output.

Effects of Changes in Climate in Low-Income Regions

As noted earlier, studies on greenhouse warming outside Europe and North America are fragmentary, and it is not possible to come to any general conclusions at this time. In the survey mentioned above, respondents were asked to estimate the impact on the top and bottom quintiles of world income distribution. In general, all the respondents believed that the lowest quintile would be more seriously affected than the top quintile. The estimated mean ratio of the bottom quintile to the top quintile ranged from 1.75 to 10.0; that is, the economic damage to the bottom quintile from a 3°C warming would be between 1.75 and 10 times the damage to the top quintile.

A review of the sparse literature on climate change in developing countries gives some flavor of the results. Liverman and O'Brien (1992), who use projections from five climate models to estimate the impact of global warming on Mexico, conclude that "soil moisture and water availability may decrease over much of Mexico." Although this conclusion is consistent with the quantitative findings, it is not actually a result of the model.

A second study (World Bank 1992), investigating a global-warming scenario for China in 2050, concludes that the prevalence of triple cropping will rise and notes that the diversification brought about by increased multiple cropping would appear to be favorable. The effects on precipitation and runoff patterns, however, may offset this benefit to agriculture. Again, explicit economic impacts were not assessed.

The results of Reilly and Hohmann (1993) are surprising. Assuming some adaptation and CO₂ fertilization, the economic effects on poorer countries (less

Table 1. Estimates of the Impact of Global Warming
(billions of 1988 dollars)

Sector	United States				Global	
	Nordhaus	Cline	Fankhauser	Other	Fankhauser	Other
<i>Heavily affected sectors</i>						
Agriculture	1	15.2	7.4	1.2	39.1	12.3
Coastal areas	10.7	2.5	2.3			
Energy	0.5	9.0	0.0			
<i>Other sectors</i>						
Wetland and species loss	—	7.1	14.8			
Health and amenities	—	8.4	30.3			
Other	—	11.2	12.1			
Total	38.1					
Total	50.3	53.4	66.9			
Total as percentage of output	1.0	1.1	1.3		1.5	2.8 ^a

Note: Blanks denote not available.

a. From the author's survey of experts.

Sources: Nordhaus 1991; Cline 1992; Fankhauser 1992; for agriculture under "Other," Reilly and Hohmann 1993.

than \$500 per capita annual income) range from \$0.2 billion to \$15 billion a year. (Baseline gross output in these regions is about \$1 trillion.)

Three general factors should be weighed in evaluating greenhouse warming in developing countries. First, these countries tend to devote a larger fraction of their economies to agriculture, especially rainfed agriculture, and thus are more subject to the vagaries of climate change. Economies classified by the World Bank as "low-income" reported that 31 percent of GDP was produced in the agricultural sector in 1987; these countries have a combined total population of 2.8 billion. There is no strong presumption that the net impact of climate change will be negative everywhere, but the dependence on agriculture implies a larger economic exposure to climate change.

Second, the fertilizing effect of atmospheric CO₂ is a potentially strong mitigating factor for agricultural nations. A natural fertilizer, CO₂ has been used in greenhouses to stimulate plant growth and is particularly important for forest trees, rice, wheat, potatoes, and beans. Moreover, it appears to be particularly important in areas where water is a limiting factor—a major concern because warming may result in reduced soil moisture. The extent and quantitative importance of CO₂ as a fertilization agent are controversial, but the balance of the evidence is positive.

A third issue, for which there seems to be little mitigating offset, is the potential for a rise in sea level. Scientific evidence suggests a potential rise of somewhere between negligible and half a meter in the next century (apart from any geologically induced rise or fall). This would create an environmental catastro-

phic; coastal regions tend to be heavily populated and highly productive and are home to a significant fraction of the world's capital infrastructure. Given the slow pace of the advance of the sea level, however, intelligent planning for defense or retreat could reduce the costs significantly.

This discussion emphasizes above all the tenuousness of our understanding of the relationships not only between economic development and climates present but also between economic prospects and climates future. If the mainstream scientific view proves correct, substantial global warming is inevitable over the next century even if stringent control measures are taken; the only question is whether the extent of global temperature rise will be modest (say in the 1° to 2°C range over a century) or large (more than 3°C over a century). Pasteur observed that chance favors the prepared mind, and in this risky area much remains to be prepared.

Balancing Costs and Benefits of Emissions Controls

The greenhouse effect is the granddaddy of public goods problems—emissions will affect climate for centuries to come. Because of the climate externality, individuals will not produce the efficient quantity of greenhouse gases. An important goal of economic research is to examine policies that will find the right balance between the costs of actions to slow climate change and the benefits of reducing future damage from such changes.

The benefits of reducing emissions are realized when lower emissions reduce future climate-induced damages. To translate this into a *marginal benefit* function, we trace the emissions through GHG concentrations to economic impacts and then take the present value of the impact of an emission of an additional unit.

The *marginal cost* of emissions reduction portrays the costs that the economy undertakes to reduce a unit of GHG emissions (or the equivalent in other policies that would slow greenhouse warming). A wide variety of approaches are available to slow climate change. Most policy discussion has focused on reducing CO₂ emissions by reducing the consumption of fossil fuels through energy conservation, nonfossil energy sources (some would even contemplate nuclear power), and other measures. Such policies could be implemented through carbon taxes, although some observers prefer regulations such as tradable emissions permits. Other approaches include reforestation to remove CO₂ from the atmosphere and more stringent controls on CFCs. Another option definitely not in the environmentally correct package would be to offset greenhouse warming through climatic engineering, primarily through measures to change the albedo (reflectivity) of the earth.

From an economic point of view, cost-beneficial policies are ones in which the marginal costs are balanced with the marginal benefits of emissions reductions. The pure market solution is one with no emissions reductions; the marginal benefits are far above the zero marginal costs. Whatever the approach, economists emphasize the importance of cost-effectiveness—that is, structuring poli-

cies to get the maximum reduction in harmful climatic change for a given level of expenditure. Cost-effectiveness requires that marginal abatement costs be equalized for every process of production and consumption and in every region; the stronger cost-benefit test requires that these costs equal the marginal benefits from slowing climate change.

Sketching the optimal policy demands little more than pencil, paper, and a rudimentary understanding of intermediate economics. To move from theory to useful empirical models, however, requires the development of a wide variety of empirical economic and geophysical models. Work has progressed to the point where economics and natural science can be integrated to estimate optimal control strategies.

Nordhaus (1991) contains a simple cost-benefit analysis for determining the optimal steady-state control of CO₂ and other greenhouse gases on the basis of a comparative-statics framework. This study came to a middle-of-the-road conclusion that the threat of greenhouse warming was sufficient to justify low-cost steps to slow the pace of climate change. A more complete elaboration uses what I call the DICE model, shorthand for a dynamic integrated model of climate and the economy (see Nordhaus 1993; complete documentation and analysis are in Nordhaus forthcoming). The model calculates the optimal path for both capital accumulation and reduction of GHG emissions in the framework of the Ramsey (1928) model of intertemporal choice. The resulting trajectory can be interpreted as the most efficient path for slowing climate change given inputs and technologies; an alternate interpretation is as a competitive market equilibrium in which externalities or spillover effects are corrected using the appropriate social prices for GHGs.

The model questions whether it is better to consume goods and services, invest in productive capital, or slow climate change through reduction of GHG emissions. The optimal path is one that maximizes an objective function that is the discounted sum of the utilities of consumption per capita. Consumption and investment are constrained by a conventional set of economic relationships (Cobb-Douglas production function, capital-balance equation, and so forth) and by a novel set of aggregate geophysical constraints (interrelating economic activity, GHG emissions and concentrations, climate change, costs of abatement, and impacts from climate change). The impact function is based on the discussion in the preceding section, while other relationships are drawn from sources in economics and the natural sciences.

To give the flavor of the results, we will consider the economic optimum and compare it with two alternative policies that have been proposed by governments or by the environmental community: stabilization of GHG emissions at 80 percent of 1990 levels, and stabilization of climate so that the change in global average temperature is limited to no more than 0.2°C per decade, with an ultimate limit of 1.5°C.

Solving the model for the three policies produces a time sequence of consumption, investment, limitation of GHG emissions, and carbon taxes. The carbon

taxes can be interpreted as the taxes on GHGs (or the regulatory equivalent—say, in auctionable emissions rights) that would lead to the emissions levels required to attain the policy objectives described in the preceding paragraph.

Table 2 illustrates the results of the model runs. The first column shows the necessary reductions in emissions for GHGs (including CO₂ and CFCs). The second column shows the estimated carbon taxes necessary to produce the emissions reductions in a market economy. For calibration purposes, a carbon tax of \$100 a ton would raise coal prices in the United States by about \$70 a ton (or 300 percent), would increase oil prices by about \$8 a barrel, and would raise about \$200 billion in revenues (before taking account of emissions reductions). The economic optimum produces relatively modest carbon taxes, rising from about \$5 a ton carbon to about \$20 a ton by the end of the next century. The stabilization scenarios require much more stringent restraints. For emissions stabilization, the carbon tax would rise from about \$40 a ton carbon currently to about \$500 a ton carbon late in the next century; climate stabilization involves a rise in carbon taxes from more than \$100 a ton today to nearly \$1,000 a ton by the end of the next century.

We can also inquire into the estimated net economic impact in the model of alternative approaches. For the global economy, the economic optimum has a value over no controls of \$270 billion (in terms of the discounted present value measured in 1990 consumption). Stabilizing emissions at 80 percent of 1990 levels leads to a net-present-value loss of about \$11 trillion relative to the optimum, while attempting to stabilize climate would have a net-present-value cost of about \$30 trillion. If these figures are annualized at a discount rate of 6 percent, the outcomes for the three policies are, respectively, a gain of 0.8 percent and losses of 3 and 9 percent of today's annual gross world output.

Several other economic studies have been made of efficient approaches to slowing global warming. Research by Manne and Richels (1990, 1992), Peck and Teisberg (1992), and Kolstad (1992) reach conclusions roughly similar to those reported here. The studies by Jorgenson and Wilcoxon (see especially 1991) show a lower set of carbon taxes needed to stabilize GHG emissions than those shown here, in part because of induced innovation.

Cline (1992), Peck and Teisberg (1991), and Kolstad (1992), as well as earlier studies by Nordhaus (1979, 1991), also determine the optimal emissions control rates and carbon taxes. With the exception of Cline, all the earlier studies show optimal policies in the general range of those determined here. Cline, by contrast, proposes much higher control rates, primarily because his result is not grounded in explicit intertemporal optimization and assumes a rate of time preference that is lower than would be consistent with observed real interest rates.

In the implementation of a policy to slow climate change, issues will arise concerning the distribution of the burden among different countries. If it is decided to reduce GHG emissions, the criteria that might be proposed for burden sharing are many. Should the reductions be parceled out on the basis of income

Table 2. Alternative Policies for Slowing Climate Change
(1990 dollars)

<i>Policy options</i>	<i>Control rate, 1995 (percent)^a</i>	<i>Carbon tax, 1995 (dollars)^b</i>	<i>Annualized global impact (billions of 1990 dollars)^c</i>
Optimal policy	8.80	5.24	16.39
20 percent reduction of emissions from 1990 levels	30.80	55.55	-762.50
Stabilization of climate	47.40	125.80	-1,962.00

a. Reduction of greenhouse gas emissions below baseline.

b. Tax on greenhouse gas emissions in dollars per ton of carbon dioxide equivalent emissions, carbon weight.

c. Present value of difference between base run and no-control case, annualized at a 6 percent real interest rate.

Source: Author's calculations.

or of wealth? On the basis of consumption, production, or reserves of fossil fuels? Should energy-efficient solutions be treated more favorably than inefficient solutions? Should the carbon quotas be distributed on the basis of population, land area, coastline, or current or future gross national product? Should areas that grow rapidly be penalized or favored? Should emissions reductions be targeted to those whose past or present emissions are causing climate change or to those who will benefit from the reductions? (A plea for justice for the poorer nations, along with a critique of current approaches, is contained in Parikh 1992.) There are clearly no "right" answers to these political questions, but judging from the performances of the nations at the 1992 "Earth Summit," distributional quarrels may well be so loud that they drown out pleas for discussion of sensible policies.

Uncertainties and Anxieties

Most economic studies of climate change are based on smooth and gradual warming. The conclusion that emerges from most of these studies suggests that the best course is to impose modest restraints and move to other, more pressing, problems. Given the high costs of controls and the modest projected impacts of a 1° to 2°C warming over the next half century, how high is global warming on an international agenda that includes exploding population in the South, nuclear proliferation in the Middle East, collapsing economies in the East, increasing cycles of poverty and drug use along with stagnating incomes in the West, and outbreaks of violence and civil war almost everywhere?

Given other urgent concerns, we might conclude that global warming should be demoted to a second-tier issue, or perhaps even lower. Yet even for those who downplay the urgency of dealing with climate change, there remains a deep anxiety about future uncertainties and surprises. Scientists raise the specter of shifts in currents turning Europe into Alaska, of midcontinental drying that

transforms grain belts into deserts, of great rivers drying up as snow packs disappear, of severe storms wiping out whole populations of low-lying regions, of surging ice sheets raising ocean levels by 20 to 50 feet, of northward migration of old or new tropical pests and diseases into the temperate regions, of environmentally induced migration overrunning borders in search of livable land. Given the potential for catastrophic surprises, perhaps we should conclude that one of the major concerns, if not *the* major concern, lies in the uncertainties and imponderable impacts of climate change rather than in the smooth changes foreseen by the climate models.

Once we open the door to consider catastrophic changes, a whole new debate begins. If we do not know how human activities will affect the thin layer of life-supporting activities that gave birth to and nurtures human civilization, and if we cannot reliably judge how potential geophysical changes will affect civilization or the world around us, can we use the "plain vanilla" cost-benefit analysis? Should we be ultraconservative and tilt toward preserving the natural world at the expense of economic growth and development? Do we dare put human betterment before the preservation of natural systems? Should we trust that human ingenuity will bail us out if nature deals us a nasty hand?

Faced with this dilemma, we might be tempted to say that such questions are beyond the capability of rational analysis and turn the decisions over to absolutist approaches. But in fact, natural and social sciences have an important role to play in analyzing potential future outcomes and delineating potential responses. Society often requires that decisions be made in the absence of complete information, whether the decisions be in military strategy, oil drilling, or research and development. In each case, a reasoned decisionmaking process involves listing the events that may occur, estimating the consequences of the events, judging the probabilities that each of the events will occur, weighing the expected value of the consequences against the expected costs under different courses of action, and choosing the action that maximizes the expected value or utility of the outcome. Reasoned decisionmaking under uncertainty is no different for climate-change policy than for other areas, although it may be more complex and may require mere crossing of traditional disciplinary boundaries.

Some might say that this calculus of costs and benefits is fine for the rich, who possess plenty of everything and have the luxury of planning for the next millennium. The logic is less compelling for poorer regions that cannot today afford to take food from the hungry, deny schooling to the poorly trained, curb public health programs for the sick, and refuse transportation, shelter, and infrastructure to the dispossessed. Why, it might be asked, should the current generation, with all its ailments and quarrels, be burdened with a costly agenda for dealing with changes in climate—an agenda that will produce some ill-defined and conjectural benefit for future generations that are likely to be much better off and better able to adapt to future shocks? The answer could be that societies, like people, must be careful in their choice of enemies.

Notes

1. A notable exception is a study by Kamarck (1976), which observes that the tropical regions are so burdened by laterite soils, weeds, locusts, parasites, and heat stress that, "all other relevant factors being equal, the pace of development in tropical countries tends to be slower."

2. For example, see Streeten (1972), Nafziger (1990), and Todaro (1991). Perhaps the most striking irony is the treatment of the subject by Todaro. He states, "*It is a historical fact that almost every successful example of modern economic growth has occurred in a temperate-zone country*" (italics in original). He then takes nine lines of a large tome, with not a single reference, to speculate on this remarkable "fact."

3. A nontechnical description of the science underlying the greenhouse effect appears in National Academy of Sciences (1992). For a thorough survey, full of interesting figures and background, see the report by the Intergovernmental Panel on Climate Change (IPCC 1990).

4. For example, an earlier study of the impact of global warming on U.S. agriculture by Adams and others (1988) found that a doubling of CO₂ would result in an annual loss to U.S. agriculture of \$34 billion. After taking into account a limited adaptive response by farmers, along with international adjustments in production and consumption, Reilly and Hohmann put these losses at an estimated \$0.5 billion–\$2.7 billion. Even more dramatic results were found in Mendelsohn, Nordhaus, and Shaw (1993), in which the economic impact of a doubling of CO₂, with full adaptation but without international trade or CO₂ fertilization, was estimated to be between –\$0.7 and +\$2 billion a year (in 1982 prices).

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COMMENT ON "CLIMATE AND ECONOMIC DEVELOPMENT,"
BY NORDHAUS

Dale W. Jorgenson

In 1896 Svante Arrhenius, a distinguished Swedish physicist, calculated that a doubling of atmospheric concentrations of carbon dioxide in the earth's atmosphere would increase global mean temperatures by 4 to 6 degrees C. In 1990 the Intergovernmental Panel on Climate Change (IPCC), an international group of leading atmospheric scientists, estimated that a doubling of global concentrations of carbon dioxide would increase temperatures by 1 to 5 degrees C in long-run equilibrium and that temperatures would rise 3 to 6 degrees C by 2100, with a best guess of slightly over 4 degrees C.

This brief history of scientific findings on global climate change illustrates an important point: the critical features of the phenomenon are relatively easy to grasp. Arrhenius' calculations, although based on a sophisticated application of well-known physical principles, can be described in today's language as "back-of-the-envelope," since they were carried out long before the invention of the computer. Even so, the results demonstrated the importance of the warming effect of carbon dioxide and other "greenhouse" gases and explained why our planet's atmosphere is hospitable to life, including human life.

The estimates prepared by the IPCC, by contrast, are based on a summary of the latest results from elaborate computer-based simulation models of global climate, known as global circulation models (GCMs). GCMs employ physical principles similar to those of Arrhenius but incorporate much greater detail and more up-to-date estimates of the underlying physical constants. Although GCMs have produced much valuable information about present and future climates, Arrhenius got the greenhouse effect of carbon dioxide accumulations in the atmosphere about right.

As Nordhaus emphasizes, this field of economics is in its infancy—definitely closer to Arrhenius's stage than to that of the GCMs—but the basic outlines of the problem are accurately described in his paper. The results are at sharp variance

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with policy approaches now in common use and suggest that economists will have an uphill battle in bringing their perspective to bear on global climate policy.

The results of Nordhaus's research to date are summarized in tables 1 and 2 in his paper. A doubling of carbon dioxide concentrations in the atmosphere over the next century could result in a substantial economic loss. For the United States the effect could be equivalent to a reduction of 1.0 to 1.3 percent of gross national product. One estimate puts global damage at 1.5 percent of world product. Much careful work remains to be done to refine these estimates, but the broad outlines are clear enough; global climate change could impose a loss of the order of magnitude of one year's growth.

Nordhaus shows that an optimal global climate policy would produce benefits, relative to no controls, of 0.8 percent of world product, or half the total loss attributable to climate change. This policy could be implemented by imposing a world carbon tax beginning at \$5 a ton and gradually rising to about \$20 a ton by the end of the next century. This would slow the rate of increase of carbon dioxide emissions but would allow both emissions and atmospheric concentrations to rise well above historical levels.

Nordhaus's proposal stands in stark contrast to the global climate policy discussed at the "Earth Summit" in Rio de Janeiro in June 1992, which focused on a goal of stabilizing emissions of carbon dioxide at 1990 levels. This goal has been analyzed in Nordhaus (1992), using the same modeling framework as in his determination of an optimal climate change policy. I have already pointed out that the optimal policy produces a *gain* relative to a policy of no controls, cutting the cost of climate change in half. By contrast, the goal of stabilizing emission, if achieved at minimum cost, would produce an annual *loss* equivalent to 1.6 percent of world product, thereby doubling the loss from climate change. More stringent goals, such as those presented in table 2 of Nordhaus's paper, have also been discussed. These include stabilizing emissions at 20 percent below 1990 levels and stabilizing climate, which would imply declining concentrations of greenhouse gases in the atmosphere at some time in the future.

The costs of the more ambitious goals are staggering. Stabilizing global climate, for example, would bring about a loss of 9 percent of world output, or several times the cost of no controls. It is important to point out that the stabilized climate would record an average global temperature of 1.5 degrees C above current climate, requiring substantial adaptation to the new climate. In short, Nordhaus has made a major contribution to our understanding of global climate policy by implementing a cost-benefit approach that takes into account the relevant economic and physical data about the interaction of future economic growth with emissions of greenhouse gases.

The question is, in the absence of a world government, how could a global carbon tax be successfully implemented? One option being discussed is the use of internationally tradable permits for carbon dioxide emissions. A binding international agreement to implement such a scheme might or might not be

combined with efforts to redistribute wealth. This is the aspect of global climate policy that has attracted the attention of many development economists, especially those schooled in the "North-South" debates of recent decades. Of course, the use of global climate policy for redistribution becomes substantially less attractive with Nordhaus's optimal global climate policy because far less money would be involved.

Unfortunately, "official" discussions of climate change at the "Earth Summit" or within individual countries have not been informed by such straightforward calculations as those in Nordhaus's paper. The key economic concepts, such as a carbon tax and internationally tradable permits, have been widely discussed, but almost exclusively in qualitative terms. The goal for economic research identified by Nordhaus is to determine the right balance between costs and benefits in setting objectives for global climate policy. Two decades of public debate on environmental issues in the United States and elsewhere have revealed that this goal is deceptively easy to state but almost impossible to achieve. With a few exceptions, economists have chosen to limit their analysis to the use of economic incentives to achieve objectives determined by others. The official U.S. position, advanced by the Bush administration in Rio de Janeiro, is a textbook illustration of this approach.

In fact, the situation is worse than I have suggested. Market-based or economic incentives are faring poorly in the intellectual competition with "command-and-control" approaches that focus on legal regulations and engineering solutions to limit greenhouse gas emissions. Command-and-control policies, now thoroughly discredited in the formerly socialist economies, survive in current debates over global climate policy in the so-called market economies. Cost-benefit analysis of the type Nordhaus has successfully applied to global climate policy is conspicuous in practical policy debates, such as those now under way in the United States, mainly by its absence.

Judging from the discussion at the "Earth Summit"—and its aftermath—it is possible that the economic point of view will once again be excluded from the environmental policy debate. My own preliminary estimate is that future development of the economics of global climate change will reveal Nordhaus in the role of Svante Arrhenius in setting the agenda for future scientific research. I think his paper and the work that it summarizes contain the appropriate starting point for all future discussion of this important environmental issue.

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**COMMENT ON "CLIMATE AND ECONOMIC DEVELOPMENT,"
BY NORDHAUS**

Robert H. Williams

I do not find convincing Nordhaus's assessment that the impacts of global warming will be minor. Moreover, I think he has greatly overestimated the costs of making major reductions in greenhouse gas emissions.

Nordhaus's calculations, using his DICE model (Nordhaus 1992), do not take into account the large uncertainties in the impacts—for example, the potential for converting grain-producing regions of midcontinents into deserts, the intensification of hurricanes, the creation of environmental refugees, and political instability—although Nordhaus does acknowledge such possibilities. While poor countries are likely to be the most vulnerable to the potential adverse impacts of global warming and the least capable of taking corrective action, Nordhaus simply argues that poor countries have more pressing problems. Perhaps the most serious shortcoming of Nordhaus's assessment of impacts is his failure to take into account the long-term impacts of prospective greenhouse gas emissions during the next century.

Unfortunately, the long-term impacts of the buildup of greenhouse gases in the atmosphere have been given little attention in climatic modeling efforts. The "business-as-usual" emissions scenarios developed in the assessments by the Intergovernmental Panel on Climate Change of climatic impacts of greenhouse warming (IPCC 1990, 1992) lead to a quadrupling of the atmospheric concentration of the CO₂-equivalent greenhouse gases relative to pre-industrial levels near the year 2100. These assessments do not explore the implications of this quadrupling beyond the year 2100. However, in a global ocean-atmospheric modeling analysis, Manabe and Stouffer (1993, 1994) explore the implications over a 500-year period of a scenario in which the atmospheric concentration of CO₂ (a) quadruples in roughly the time frame envisioned for greenhouse gas quadrupling in the IPCC business-as-usual scenario and (b) remains constant

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thereafter. In assessing impacts it is essential to take a long-term view of near-term actions—first because the ocean-atmosphere system will not have fully responded to the increased greenhouse gas concentration level in a hundred years, as a result of the thermal inertia of the oceans, and second, because near-term releases of greenhouse gases are irreversible.

One of the serious consequences of a quadrupling of the CO₂ concentration, according to the findings of Manabe and Stouffer, is a virtual cessation of the south-north overturning in the world's oceans, caused by the capping effect of less dense fresh surface water in higher latitudes as a result of increased precipitation in the warmer, wetter atmosphere. Another consequence is a sharp rise in sea level: 1.8 meters just from the thermal expansion of the warmed sea water, plus a further large increment caused by the melting of continental icesheets (mostly in Greenland and the edge of Antarctica). The latter contribution to sea level rise depends on the extent of refreezing, which is uncertain. With no refreezing, the total sea level rise (thermal expansion plus ice sheet melting) in 500 years would be about 9 meters; if only half of the meltwater eventually reaches the oceans, the total sea level rise would still be about 5 meters. In any case, the prospective sea level rise would be a very serious impact. Furthermore, the 7° C increase in the global mean air temperature associated with a quadrupling of CO₂ is nearly as large as the inferred difference between today's climate and the very warm Cretaceous period 65 million–90 million years ago. Although important uncertainties remain and no effort has yet been made to put a dollar value on these prospective global changes, the implications of this modeling exercise, even if only partially correct in predicting the behavior of the ocean-atmosphere system, are daunting.

It would be foolish to ignore such potential consequences—especially in light of the prospect that the costs of reducing emissions are likely to be far less than Nordhaus has estimated. There are major opportunities for reducing CO₂ emissions from fossil fuel burning at low cost, through the pursuit of opportunities for making more efficient use of energy and the accelerated development and widespread adoption of various renewable energy technologies. The possibilities are illustrated by a renewables-intensive global energy scenario (RIGES) developed in a study to assess the prospects for renewable energy (Johansson and others 1993). The assessment, commissioned by the United Nations Solar Energy Group for Environment and Development as an input to the 1992 United Nations Conference on Environment and Development (UNCED), was carried out by more than fifty of the world's leading experts on renewable energy from eleven countries. The options studied included hydroelectric, wind, solar thermal, photovoltaic, and geothermal power; electricity from biomass; alcohol fuels and hydrogen from biomass; and hydrogen produced electrolytically from wind, photovoltaic, and hydroelectric power sources. The RIGES shows the potential impacts on the global energy system for the years 2025 and 2050 of the accelerated development of the more promising renewable technologies.

The energy demand scenario adopted for the exercise was one of several constructed by the Response Strategies Working Group of the IPCC (1990). This

scenario—a set of regional projections of demand for electricity and for gaseous, liquid, and solid fuels used directly—is characterized by “high economic growth” and “accelerated policies” and is based on an assumed doubling of world population and an eightfold increase in gross world economic product between 1985 and 2050. Energy demand grows more slowly than economic output because of the accelerated adoption of energy-efficient technologies. The demand for fuels used directly is projected to increase 30 percent between 1985 and 2050, and demand for electricity, 265 percent.

Renewable technologies are unlikely to succeed unless they are a part of a program designed to minimize the overall cost of providing energy services. Thus the energy-efficiency assumptions underlying the accelerated policies scenario are consistent with the objectives of the RIGES. Because a slowly growing economy generally provides a poor theater for innovation and RIGES calls for rapid innovation in the energy sector, the high-economic-growth variant of the accelerated-policies scenario was chosen.

Energy supply mixes consistent with estimates of fossil fuel and renewable natural resource endowments and expected relative prices were constructed, with overall supply levels matched to the IPCC demand projections, for each of eleven world regions. The purpose of the exercise was not to forecast how a renewables-intensive energy future would evolve but rather to see how it might evolve under appropriate policies if society should decide that a renewables-intensive energy future is desirable. The authors assumed that renewable technologies would capture markets whenever (a) a plausible case can be made that renewable energy is no more expensive on a life-cycle-cost basis than conventional alternatives and (b) the use of renewable technologies at the levels indicated will not create significant environmental, land use, or other problems. The authors did not take into account in the economic analysis any credit for non-market benefits of renewables but assumed that market barriers to the wide adoption of renewable energy technologies would be removed by appropriate national and international policies.

In the RIGES renewable energy provides nearly three-fifths of global primary energy requirements by 2050, with biomass accounting for about three-fifths of all renewables. The fraction of electricity generated by renewables is about the same; half of this comes from intermittent renewables (wind, photovoltaic, and solar thermal-electric sources) and about a quarter each from hydropower and biomass. If the RIGES could be implemented, global CO₂ emissions from the energy sector in 2050 would be reduced by about 25 percent relative to 1985 emissions, and this reduction would be achieved with no increase in the cost of providing energy services. Moreover, because energy demand would be much lower than under business-as-usual conditions, and because of increased competition in energy markets from fuels derived from renewable sources, world energy prices would be lower than under business-as-usual conditions.

There are uncertainties underlying the RIGES, especially since many of the needed technologies are not yet commercially available. But all the technologies

involved are at sufficiently advanced states of development that technical and economic performance can be described with a reasonable degree of confidence. The key to realizing the RIGES is a set of public and private sector policies aimed at exploiting the cost-effective potential for more efficient use of energy and accelerating the development and commercialization of a wide range of renewable energy technologies.

Policies designed to rationalize energy prices to reflect the true costs of energy, as well as various measures for dealing with market imperfections, are needed to promote the more efficient use of energy. U.S. experience offers examples of the latter: (a) energy efficiency standards (such as those for automobiles and consumer appliances); (b) the federal mandate that electric utilities purchase, at prices equal to the avoided costs, electricity produced by qualifying cogenerators; (c) the new federal government-industry partnership that seeks to bring to commercial readiness in a decade a new generation of cars that are three times as energy-efficient as today's; and (d) state regulations mandating that utilities practice integrated resource planning—that is, pursue the most cost-effective mix of investments in new supply and energy efficiency improvements to meet the demand for expanded energy services.

The desirability of accelerating the pace of development of renewable energy technologies stems not only from a wide range of external benefits of renewables, of which the potential for reducing greenhouse gas emissions is only one (Johansson and others 1993) but also from the prospect of substantial direct economic benefits. This prospect arises from the special characteristics of a wide range of renewable energy technologies that distinguish them from fossil fuel and nuclear technologies.

Large fossil fuel and nuclear energy facilities require extensive construction in the field, where labor is costly and productivity gains are difficult to achieve. The long construction periods for these systems also make it difficult to cut costs through "learning-by-doing." In the 1970s and 1980s production bottlenecks—arising from the practical difficulties of standardizing designs for large energy production facilities, from tougher environmental regulations, and from growing public opposition to the construction of new facilities—often meant that energy from new plants was more costly than that from old plants.

In contrast, the small unit sizes of most renewable energy equipment facilitate cost cutting as a result of both learning-by-doing and technological improvements. This equipment can be constructed in factories, where it is easier to apply modern manufacturing techniques that facilitate cost reduction. Also, because with small-scale equipment the time required from design to operation is short, needed improvements can be identified by field testing and quickly incorporated into modified designs. As a result of such learning-by-doing, many generations of marginal technological improvements can be rapidly introduced.

For technologies with these attributes and with good prospects for technological improvement, it will often be worthwhile to develop them as quickly as is feasible. A detailed case study for photovoltaics has been carried out to illustrate

this point (Williams and Terzian 1993). It is shown that if photovoltaic technology is developed rapidly through enhanced support for research and development and market stimulation subsidies, costs fall much more quickly than under business-as-usual conditions, and the discounted present worth of future net benefits (considering only the net savings to consumers from reduced electricity bills as a result of the displacement of fossil energy) is very large in relation to the subsidies. An accelerated-development scenario is described that leads to 400,000 megawatts of installed photovoltaic capacity worldwide by the year 2020 (consistent with what is needed for the RIGES). For this scenario, the present value of net future benefits is estimated to be of the order of \$100 billion worldwide, as against costs of \$3 billion for the needed market incentives and a substantial increase in the photovoltaic R&D effort (which presently costs OECD governments about \$200 million per year).

Of course, one cannot be sure that any one renewable energy technology will be successfully deployed in the market as a result of such an effort. However, the modular scale of photovoltaic and other renewable technologies makes it generally possible to pursue a diversified portfolio of options to reduce risk. This is in sharp contrast to the situation for large-scale fossil and nuclear fission and fusion technologies; because the necessary R&D and market stimulation subsidies tend to be very large, society can afford to explore only a narrow range of alternative options simultaneously.

The World Energy Council has also estimated what it will take to commercialize photovoltaic and various other renewable technologies (WEC 1993). In the case of photovoltaics the WEC estimates a market stimulation cost of \$2.5 billion to \$4.0 billion, plus another \$5 billion for R&D. The total cost of development for a set of various renewable energy technologies is estimated at \$15 billion to \$20 billion—a trivial amount compared to what the public sector has traditionally spent on energy R&D. (For example, OECD countries spent \$100 billion, in 1992 dollars, on R&D for nuclear fission energy during the period 1977–91 and probably twice that much if expenditures for the period 1950–76 are included.) The costs of developing renewables are especially small in relation to the total subsidies provided by governments to the energy sector. For example, the market value of all U.S. government subsidies to the energy sector is estimated to have been \$36 billion in 1989, including \$21 billion for fossil fuels and \$11 billion for nuclear fission (Koplow 1993).

Not only is the benefit-cost ratio of pursuing an energy-efficient, renewables-intensive energy future likely to be very favorable for the global economy, but also the diversity of benefits offered by such an energy path would be especially important to many developing countries because it would make it easier for them to address many of the challenges Nordhaus believes are more pressing than the greenhouse problem. It is highly unlikely that the economic goals of developing countries can be realized by retracing the development paths already taken by the industrial countries. Alternative paths involving innovative solutions offer more promise. In trivializing the greenhouse challenge for developing countries, Nord-

haus overlooks the potential for energy innovation—in particular, in simultaneously addressing global warming and broad development challenges.

Developing countries need advanced technologies not just to meet environmental objectives but also to promote long-term economic growth. Some advanced technologies can be obtained by technology transfer from industrial countries. But developing countries also need technologies better tailored to their circumstances than those already in use in industrial countries. Whereas developing countries are labor rich and capital poor, many of the new technologies developed in industrial countries are labor-saving and capital-intensive. Labor-intensive, capital-saving innovative technologies—for example, various biomass energy technologies—would often be more appropriate for developing countries. Moreover, the needs for innovation are different in developing and industrial countries. Since basic materials (such as steel, cement, and glass) are needed for infrastructure building, the basic-materials-processing industries should be engines for economic growth for many developing countries. Innovations in these industries typically lead to processes that, in addition to being less costly, are cleaner and less energy-intensive and emit less greenhouse gases. Developing countries cannot depend on the industrial countries for innovations in these industries because the demand for basic materials is largely saturated in the industrial countries (Williams, Larson, and Ross 1987) and little innovative activity is going on there in the relevant industries. And finally, natural resource endowments are different; many developing countries have scant fossil fuel but abundant biomass and direct solar energy resources.

Without support from the industrial countries, energy planners in developing countries are unlikely to pursue innovative energy technologies. Faced with many pressing development challenges, these planners are reluctant to assume risks that provide only long-term payoffs. In addition, many planners have been “burned” by past efforts to transfer advanced energy (such as nuclear) technology from the industrial countries. And the development assistance community has also not been supportive of innovations for the energy sector. This policy seems to be attributable partly to the World Bank’s goal of providing loans at below-market interest rates and partly to the widely held view in the development assistance community that the infrastructure to support the innovative process does not exist in developing countries.

Such problems must be addressed, and a new climate conducive to energy innovation in developing countries must be created. The global-warming debates could very well provide the impetus needed. As a result of the UNCED process, many decisionmakers in industrial countries are coming to realize that unless there is substantial energy innovation in developing countries aimed at shifting away from high-carbon-content fossil energy sources, future energy growth in developing countries will accelerate global warming, no matter what the industrial countries do at home.

If the Global Environment Facility (GEF) were to emphasize innovative projects, such as its biomass gasification–power generation project in northeast

Brazil (Elliott and Booth 1993), the development assistance community would be off to a good start in addressing the innovation challenge. But much more needs to be done; for example, support from industrial countries is also needed to help build the infrastructure for the innovative process in developing countries.

Whereas Nordhaus believes that the impacts of global warming will be minor and that developing countries have more pressing problems to worry about, I believe that the potential impacts cannot be lightly dismissed and that the costs of addressing the greenhouse challenge can be kept to acceptably low levels. Moreover, the greenhouse issue is already forcing the North to pay more attention to the development needs of the South. It could very well provide the organizing principle needed to help the industrial and developing countries find ways to work together in identifying and pursuing the path to a sustainable world.

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COMMENT ON "CLIMATE AND ECONOMIC DEVELOPMENT,"
BY NORDHAUS

Dennis Anderson

I have two comments: one on costs, the other on benefits. But first a point of agreement. Professor Nordhaus is well justified in concluding that a much higher priority needs to be given to development in the poorer regions of the world than to addressing the greenhouse effect. When the World Bank team was drafting *World Development Report 1992*, on development and the environment, among our concerns was that influential groups in the wealthy countries, preoccupied with the greenhouse effect, would drive key problems of development off the international agenda. We argued not only that local economic—not to say local environmental—problems in developing countries were of far greater importance but that the achievement of higher living standards and economic stability in developing countries would leave them better placed to address the global-warming problem, should the need arise. That the cost-benefit studies of Nordhaus and his colleagues have helped policymakers concentrate on priorities is in itself a major accomplishment.

Nevertheless, the nature of the global-warming problem requires that precautionary policies be put in place. Nordhaus accepts this, of course, when he argues for a modest carbon tax. But I think we need to be more specific about the (precautionary) policies required and to look at costs and technical developments more critically. The following remarks also draw on the comments of Professor Williams.

Costs and Technical Developments

Along with Williams, I believe that Nordhaus has overestimated the costs of controlling carbon emissions, and I too find Nordhaus's paper to be tacitly pessimistic in its assumptions about technical progress. Even in an energy-

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efficient scenario, it seems likely that the world demand for commercial energy will rise from its present level of about 8 billion tons of oil equivalent a year to 15 billion–20 billion tons, and possibly more, over the next few decades. The main source of growth will be the developing countries; although their per capita consumption levels range from one-eightieth to one-tenth of per capita consumption in the United States, they are rising rapidly. Since 95 percent of world commercial energy demands are met by fossil fuels, and given the failure of nuclear power as a backstop technology, it is clear that addressing the global-warming problem, if the problem indeed becomes grave, will require the use of renewable energy on a large scale—such as biomass solar energy from photovoltaics and thermal-solar schemes.

As far as we can presently see, therefore, once the (very fruitful) opportunities for improving energy efficiency have been exploited, both the marginal and the average costs of addressing the global-warming problem will be determined by the costs of using renewable energy. Although other possibilities cannot be ruled out, the costs of renewables at least provide a basis for estimating marginal and average costs. Let us consider this further.

The marginal costs will likely be determined by the costs of liquid fuels. It will be difficult indeed for renewables to compete with petroleum fuels. An indication of what these costs might be is provided by the example of the fuel-cell electric vehicle, which is now under active development. Williams and others have estimated that by 2010 net costs could fall to about \$140 per ton of carbon, given a commitment to develop such vehicles. These estimates are between one-fifteenth and one-seventh of the marginal costs of \$1,000 a ton for the end of the next century quoted by Nordhaus, whose estimates make little allowance for innovation and technical progress in energy supply. (As only three words in Nordhaus's paper are devoted to nonfossil fuels, however, it is difficult to understand the basis of his estimates.)

One reason why Williams and others have estimated lower costs is that they properly allow for the thermodynamic disadvantages of the internal combustion engine. (Its technical efficiency is only about 20 percent, as compared with 60 percent for the fuel-cell electric vehicle.) If Williams and others were not to allow for this threefold gain in efficiency, their estimates of carbon taxes would also be very high, around \$900 a ton. (This is more than three times Williams's estimate of \$120 per ton because we are talking about *differences* in the marginal costs of using conventional and fuel-cell electric vehicles.) In addition, we must not overlook what might happen to fossil-fuel prices if, as is possible, energy consumption in the next century were to be five or more times the amount consumed in the present century. It seems likely, for example, that the world will eventually have to turn to more expensive synfuels sooner or later (industry is already weighing this possibility), and this too would make a difference in the calculation of costs.

Next, consider the electricity markets, which will probably account for more than half of the energy market before long. (The share is now about 40 percent,

but it continues to rise.) Two promising candidates for power generation—both especially well suited to developing countries, where solar insolutions are 2.0 to 2.5 times those in the “North”—are photovoltaic and solar-thermal technologies. The costs of both have fallen dramatically in recent years. In the case of photovoltaics, costs have declined by a factor of 50 to 100 since the early 1970s, and there are convincing engineering and economic reasons for expecting further progress (see figure 1). There is consequently much commercial interest in the development of these technologies. A perusal of the proceedings of the Photovoltaics Specialists Conference, held every eighteen months or so by the American Institute of Electronics and Electrical Engineers, also testifies to the intellectual quality of the research effort in industry and in the research establishments.

Mention should also be made of solar-thermal projects, of which about 400 megawatts worth are presently in operation in the United States at costs of around 15 cents a kilowatt-hour. The technology is modular, construction times are short, scale economies in manufacture have yet to be exploited, and there is much scope for improving conversion efficiencies. Moreover, thermal energy can be stored. There is every prospect that these technologies could begin to compete with fossil, hydroelectric, and nuclear power in high-insolation areas of the world in a decade or so. Moreover, solar energy is not a land-intensive resource; the land intensity of solar schemes is less than one-hundredth of the land intensity of, for example, the Aswan hydroelectric project in Egypt.

In sum, although we cannot be very precise as to comparative costs, we do know that they will not be too far removed from the costs of fossil fuels for electricity generation, and there is a good chance that they will eventually be lower than these costs in the high-insolation areas of developing countries. It is possible therefore that the cost estimates now being used in the climate cost-benefit models could be in error by a large order (the same could also be true of the estimates of benefits), and there is a danger that they could mislead policymakers into neglecting promising developments in the backstop technologies and thus to neglect the need for precautionary policies.

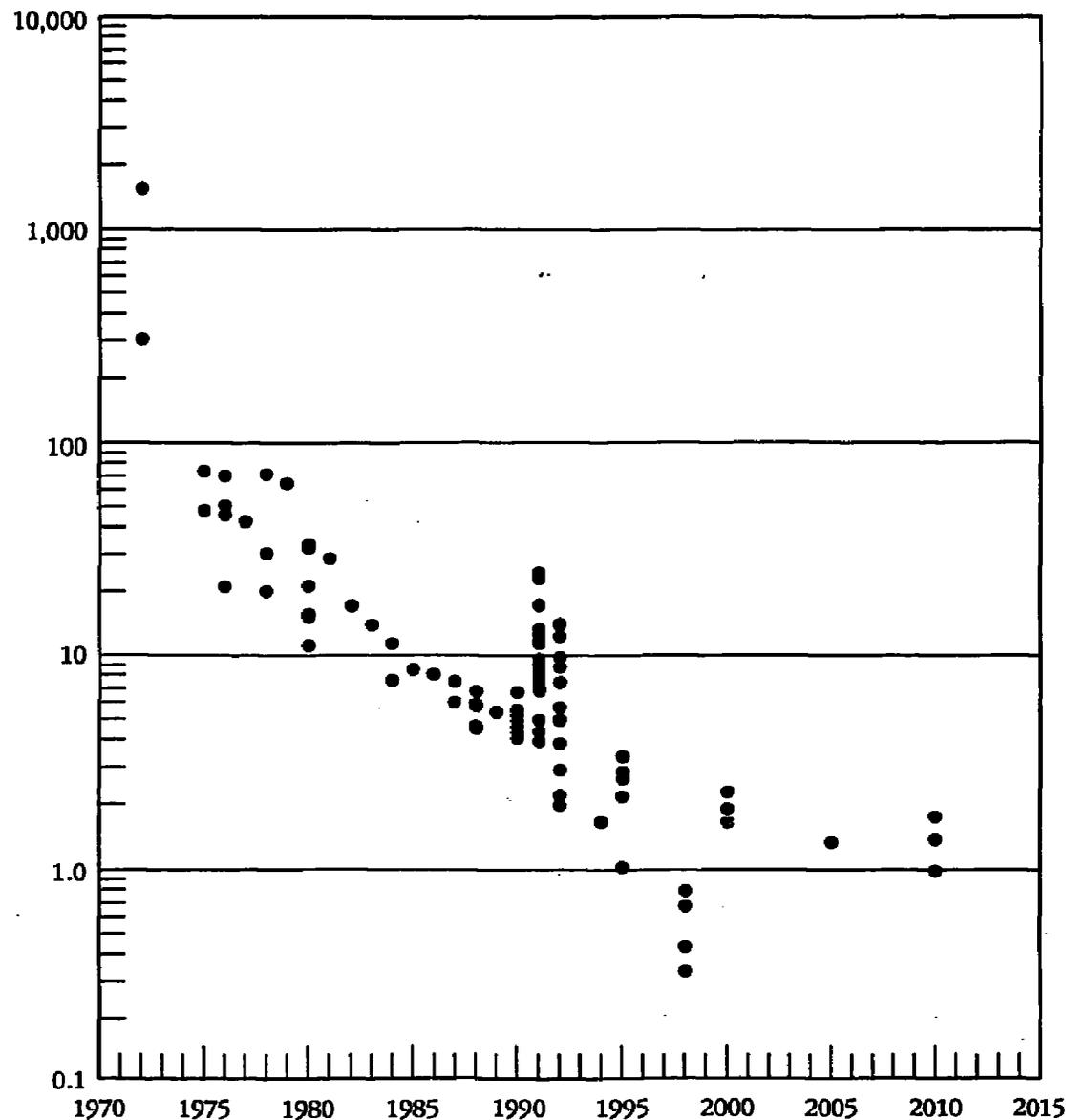
Options for Environmental Policy.

Despite the uncertainties of costs and benefits, economists need to provide more specific policy advice than they have so far. The standard recommendations are for carbon taxes, energy efficiency, and afforestation. But four other options, I think, also ought to be explored.

- *National R&D.* National research and development portfolios need to be restructured to support the emerging technologies. Public research on energy is heavily skewed toward nuclear power, provides little support for renewable energy technologies, and has yet to recognize the important technological developments that have taken place over the past two decades.

Figure 1 *Costs of the Photovoltaic Module*

Module cost (1990 dollars per watt peak; log scale)



Note: All costs for years up to and including 1992 are actual; those after 1992 are projected. The "spread" in the points reflects the spread in costs of different technologies that are at different stages of development. The size of the module used also affects cost, as does the number of modules ordered.

Source: Based on a review of more than fifty studies and manufacturers in Ahmed 1994.

- *International R&D.* Energy research should be more “outward looking.” The industrial countries tend to be narrowly nationalistic—most notably, in nuclear power. The emerging global energy problems provide an excellent opportunity for a new perspective that would serve the energy industry itself much better than have previous policies. The growth of world markets and the prospects for good commercial investments in renewable energy also argue for outward-looking programs and a greater degree of cooperation among countries. Much, I think, can be learned from the working arrangements of the Consultative Group for International Agricultural Research (CGIAR).
- *Investment incentives for innovative technologies.* Tax incentives could be provided to stimulate the use of new technologies in cases where “learning by doing” reduces costs (recall Arrow’s 1962 paper on this subject).
- *Carbon user charges.* A carbon user charge—as distinct from a carbon tax—could finance such research and development and tax incentives. Uncertainties about the greenhouse effect (not to mention the changing whims of governments) pose a financial risk for investors that a carbon tax would not adequately address, since investors would need to allow for the possibility of a reduction in such taxes because of changing perceptions as to the seriousness of the problem. It is neither reasonable, nor is it consistent with the principles of good policymaking, to expect industry to bear that portion of the risks of investment associated with uncertainties about the greenhouse effect. If industry were in fact expected to bear them, it would rightly favor the more “conservative” interpretations of the available evidence. Research and development in the backstop technologies typically has a lead time of five to ten years (indeed, ten to fifteen years if one allows for research on manufacturing methods), while the investments themselves, once in operation, may have lifetimes of twenty to thirty years. Hence the financial risks are not trivial, and the effects of even large carbon taxes could turn out to be weak. An alternative might be to “capitalize” the incentives provided by a theoretically ideal carbon emissions tax by applying the incentives directly to investments in the noncarbon technologies. To accomplish the intended effect, the incentives would also need to be made applicable at the time of investment. In this way, if policies were later reversed—say, because of new evidence on the greenhouse effect—the investments already made would at least continue to operate profitably, while plans for new investments would be scaled back without loss. Another advantage of this approach is that the user charge, over the next ten years or so, would be small, as the financial requirements for research, development, and demonstration of the technologies would necessarily be small in relation to the size of the industry. For instance, a user charge amounting to less than one-twentieth of the tax of \$100 per ton of carbon recently proposed (and then shelved) in Europe would support a substantive program of investment.

Turning to the concluding paragraph of Nordhaus's paper, I believe the above policies could indeed be weighed in good conscience by the economist, in the full knowledge that they would be likely to help—not hinder—development.

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FLOOR DISCUSSION OF THE NORDHAUS PAPER

A participant said that he had found Nordhaus's results pessimistic and his assumptions about costs high. In particular, he said, Nordhaus had ignored the probability of technological changes that would be far less expensive than the costs he was projecting. Lee Schipper also expressed skepticism about the optimal strategy Nordhaus had proposed and said he doubted that it would be possible to stabilize carbon emissions. We have a peculiar way in the United States of pushing costs off to whoever is not voting this year, he said. He wondered if a somewhat higher carbon tax would not be a good idea precisely because it would send a real price signal. We do not have a way of measuring how people respond, historically, to a permanent long-term change in energy prices; we know only what happens during the glitches. Schipper agreed that what Nordhaus had done was profound but said that somehow it had irritated many people who might otherwise be supportive, either because it was not said correctly or because it did not look correct. Nordhaus wouldn't have to move his position very far to have an excellent compromise, said Schipper. Would Nordhaus consider widening this policy hole and putting bigger bars on it, to still the critics on both the inaction and the overaction side?

Nordhaus responded first to comments about whether his results were optimistic or pessimistic. He had looked at two general sets of studies, he explained—economic models and studies that followed an engineering or technological approach. The economic modeling studies are based on equilibrium (supply and demand) approaches, such as that of Jorgenson (discussant). As a consumer of other studies, Nordhaus had tried to locate his economic modeling results in the middle of the pack. His results were actually somewhat optimistic; Jorgenson's were the most optimistic of all in the sense of projecting the lowest costs for reaching a particular emission reduction program. The engineering studies are much more optimistic in that they say that 20 to 40 percent of energy

The session was chaired by Mohamed El-Ashry, chief environmental adviser to the president of the World Bank and director of the World Bank's Environment Department.

consumption and emissions can be reduced to zero—or even negative—costs. Obviously, for the first 30 or 40 percent of emissions reductions, the engineering studies will give you lower costs. But almost all the economic models have trends that might be called exogenous reductions in energy use per unit of output, and the two basically offset each other over a twenty- or thirty-year period.

However, Nordhaus emphasized, if his results were pessimistic and we should be more optimistic, then we should have a lower carbon tax, not a higher one. If we are going to be dotting the countryside with solar thermal plants—which is not in the model now—we will not need as much of an economic incentive as a pessimistic model would imply.

Nordhaus pleaded guilty to the criticism that he had ignored innovation and technology. He simply had not found a comfortable way to include endogenous technological change, so he had assumed exogenous technological change. The Jorgenson model is the only one in existence that includes endogenous technological change, he said, and it produces different results. Certainly, if you include endogenous technological change, the optimal carbon tax should be raised because a higher tax would induce technological research and development. This is a difficult issue, he said, and no doubt we are making mistakes because the technology will be very different in the middle of the twenty-first century. If cold fusion is around and is too cheap to meter, we won't need to discuss this subject at all.

As for irritating people, Nordhaus said his role was to be an analytical economist. He would leave to others the diplomatic issues, negotiations, and compromises because once you start compromising, you lose track of where you began and of the analytical principles and start down a slippery slope. He did not want to be offensive, but in the end he felt that the role of economists, engineers, and other analysts was to present their analyses as honestly and well as they could and let the numbers fall where they may.

A participant from Argentina said Nordhaus claimed that chlorofluorocarbons (CFCs) increase greenhouse gases, but studies by the United Nations Environment Programme and the Intergovernmental Panel on Climate Change (IPCC) show the net effect of CFC emissions to be nil in relation to greenhouse gases. That must affect global models, and, to the extent that the policy of the Bush administration was simply to control CFCs, U.S. policy would have done little to limit greenhouse gases. More important is the issue of how industrial and developing countries will bear, share, or distribute the cost of different policy alternatives. Northern economists are more likely to favor a tax on energy consumption, which would be the most costly alternative for developing countries. If there is to be no transfer of payment from northern to southern countries, southern countries are likely to oppose taxes on energy consumption.