Economic Growth and Climate: The Carbon Dioxide Problem

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In contemplating the future course of economic growth in the West, scientists are divided between one group crying "wolf" and another which denies that species' existence. One persistent concern has been that man's economic activities would reach a scale where the global climate would be significantly affected. Unlike many of the wolf cries, this one, in my opinion, should be taken very seriously. The present article will first give a brief overview of the climatic implications of economic activity with special reference to carbon dioxide, and then will present possible strategies for control. A more complete report with references to the literature on climatic change is contained in Nordhaus (1976).

It is thought that the economic activities which most affect climate are agriculture and energy. Of these, the latter is probably more significant, is certainly more easily analyzed, and will be discussed here. In the energy sector, emissions of carbon dioxide, particulate matter, and heat are of significance for the global climate.

I. Energy and Climate

When we refer to climate, we usually are thinking of the average of characteristics of the atmosphere at different points of the earth, including the variabilities such as the diurnal and annual cycle. A more precise representation of the climate would be as a dynamic, stochastic system of equations. The probability distributions of the atmospheric characteristics is what we mean by *climate,* while a particular realization of that stochastic process is what we call the *weather*.

Recent evidence indicates that, even after several millenia, the dynamic processes which determine climate have not attained a stable equilibrium. One of the more carefully documented examples is the global mean temperature which over the last 100 years has shown a range of variation of five-year averages of about .6°C (see Figure 1).

At what point is there likely to be a significant effect of man's activities on the climate? Many climatologists feel that it is prudent to consider as significant the changes witnessed in the last century—the .6°C range. Although the estimates are uncertain, it is probable that for carbon dioxide such a change would come with an increase of approximately 20 percent in atmospheric concentrations over preindustrial levels. According to recent projections, we shall probably reach this level in the 1985–90 period (W. S. Broecker). For other sources—heat and particulates—the effects appear considerably later and are also more controversial.

A brief overview of the interaction between carbon dioxide and the climate is as follows: combustion of fossil fuels leads to emissions of carbon dioxide into the atmosphere. Once in the atmosphere, the residence time appears to be very long, with approximately one-half of all industrial carbon dioxide still airborne. Because of the selective absorption of radiation, the increased atmospheric concentration is thought to lead to increased surface temperatures. The most careful study to date (S. Manabe and R. T. Wetherald) predicts that a doubling of atmospheric concentrations of carbon dioxide would eventually lead to a global mean temperature increase of 3°C. The predicted temperature increase by latitude indicates that there is considerable amplification at high latitudes. Figure 1 shows the predicted change in global mean temperature as a function of time, given the predicted emissions of carbon dioxide which we will discuss in the later part

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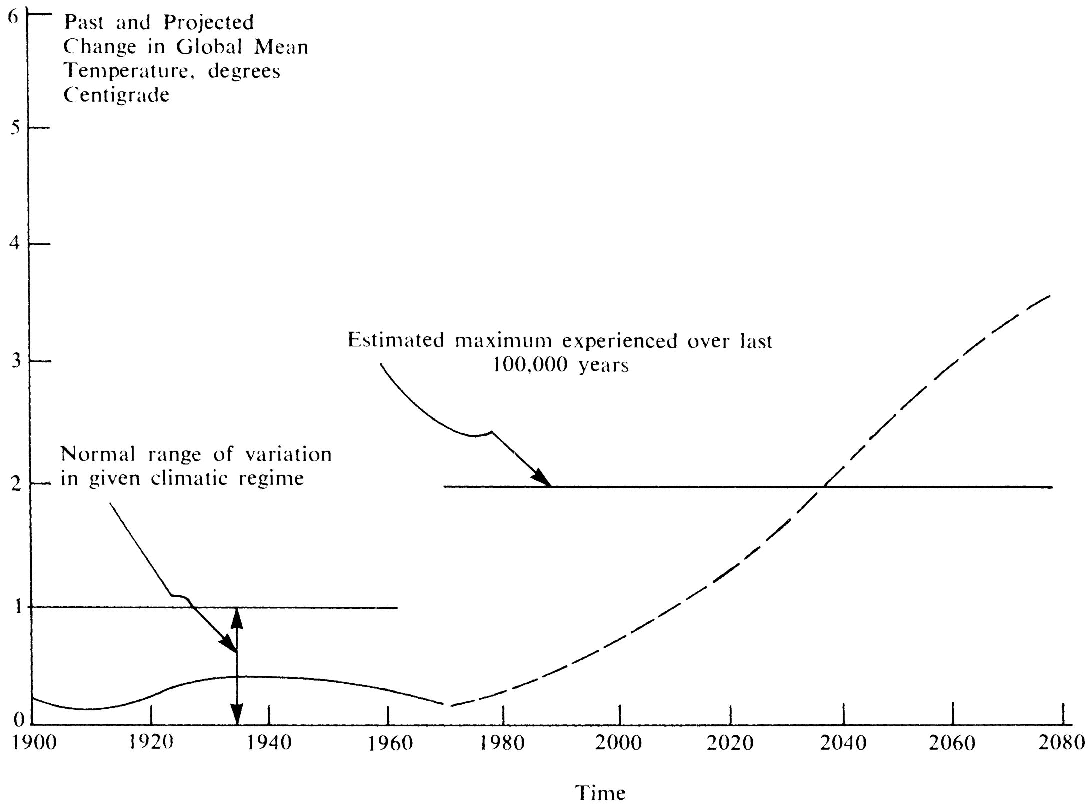

Figures up to 1970 are actual. Figures from 1970 on are projections using 1970 actual as a base and adding the estimated increase due to uncontrolled buildup of atmospheric carbon dioxide. Sources given in Nordhaus 1976).

FIGURE 1. PAST AND PROJECTED GLOBAL MEAN TEMPERATURE, RELATIVE TO 1880-84 MEAN

of this paper. It appears that the uncontrolled path will lead to very large increases in temperature in the coming decades, taking the climate outside of any temperature pattern observed in the last 100,000 years.

II. Control Strategies

The outcome just described is the effect of an uncontrolled economy-climate system. The problem is the most extreme imaginable form of external diseconomy—one in which an individual burning a fossil fuel does not take into account the climatic consequences, and thereby affects not only the global climate, but also the climate for hundreds of years in the future.

We therefore investigate strategies for control of atmospheric carbon dioxide. A control strategy involves two aspects. On a scientific and aggregate level, the feasibility of control techniques must be explored. But there must also be a way to decentralize the controls so that nations, producers, and consumers have proper incentives to implement the control strategy on an individual level.

Figure 2 gives an overview of the model used to investigate strategies. The block labeled "energy system" can be viewed as the current system of mixed market and political mechanisms. The driving variables are energy resources, income, and population. The inter-

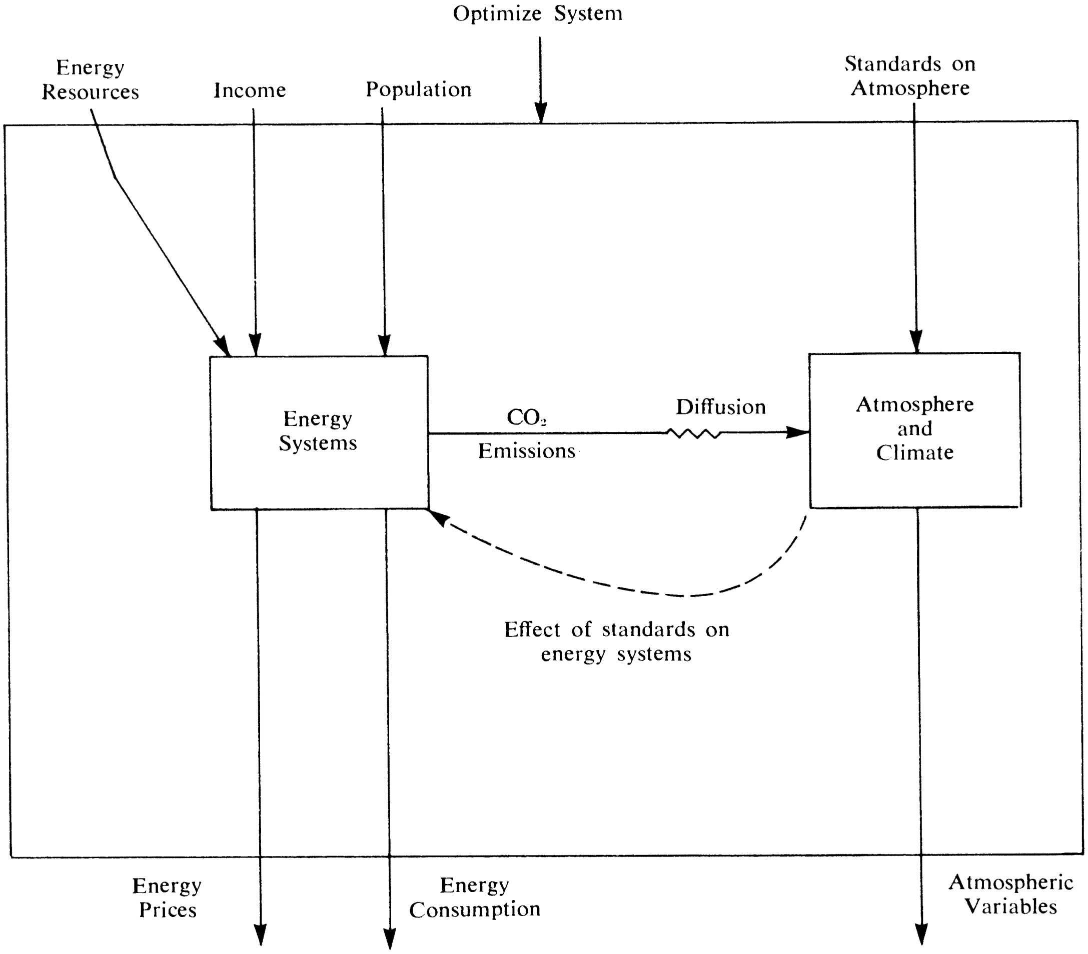

FIGURE 2. OVERVIEW OF MODEL OPTIMIZING THE ENERGY-ENVIRONMENT SYSTEM

action of supply and demand leads to a path of prices and consumption over time. To account for the externalities, such as the carbon dioxide cycle, we must take into account the emissions and distribution of the effluent. This step leads us to impose standards on atmospheric concentrations, as on the righthand side of Figure 2. By imposing standards we close the loop and force the energy system to shift the composition of supply and demand. Outside the entire system there is yet another box, indicating that the entire system is being optimized.

There are two general approaches to the problem of keeping atmospheric concentrations to a reasonable level. The first strategy—the approach examined in the present paper—is to reduce emissions of carbon dioxide. This takes place basically by substituting noncarbon-based fuels for carbon-based fuels. The second strategy is to either offset the effects of emissions of carbon dioxide or use natural or industrial processes to clean out the carbon dioxide from the atmosphere *ex post*. To avoid the odor of science fiction, we have limited controls to the first strategy.

The final question in the optimization concerns the "standards" imposed in Figure 2. Unfortunately, although considerable scientific concern has been expressed about future trends in carbon dioxide concentration, there are no attempts to suggest what might be reasonable standards. As a first approximation, however, it seems reasonable to argue that the climatic effects of carbon dioxide should be kept well within the normal range of long-term climatic variation. A doubling of the atmospheric concentration of carbon dioxide is a reasonable upper limit to impose at the present stage of knowledge. We also test the sensitivity of our results to limits of fifty percent and two hundred percent increases. We can only justify the standards set here as rough guesses and we are not certain that we have even judged the *direction* of the desired movement in carbon dioxide correctly, to say nothing of the absolute levels.

The second problem of controlling carbon dioxide is implementation on a decentralized level. Because of the externalities there are no market or political mechanisms which ensure that the appropriate level of control will be chosen. The procedure in the present paper will estimate an efficient way of allocating energy resources so as to satisfy the carbon dioxide constraint. To implement this efficient path implies that we are implicitly putting a positive price on emissions of carbon into the atmosphere, "carbon taxes," as a way of implementing the global policy on a decentralized level.

The model used to calculate the effects of imposing standards is an extension of earlier work (see Nordhaus, 1973, for a description of an early version of the energy model, and Nordhaus, 1976, for the details of the carbon model). It can be written in highly oversimplified form as follows: the energy model attempts to simulate the market allocation process. Thus, let U_{it} be the present value of the marginal utility, in terms of income, of good i in year t; c_{it} be the present value of the cost of good i in year t, both discounted at 10 percent; and let x_{it} be the level of activity. Under suitable assumptions (see Samuelson) a market allocation can be described by the mathematical programming problem:

$$(1) \qquad \underset{\{x_{it}\}}{\text{maximize}} \sum_{t=1}^{T} \sum_{i=1}^{n} [U_{it} - c_{it}] x_{it},$$

subject to constraints on the activities as well as the following resource constraints,

$$(2) \qquad \sum_{t=1}^{T} \sum_{i=1}^{n} A_{ij} x_{it} \leqq \bar{R}_j, \; j = 1, \ldots, m,$$

where A_{ij} is the content of scarce resource j per unit activity of good i, and $\bar{R}_j$ is the amount of scarce resource R_j which is available. In the actual problem examined, the goods x_{it} are composed of different energy goods (6 different fuels used in 4 different sectors), for 2 different regions of the world (United States and the rest of the world), for 10 time periods of 20 years each.

Equations (1) and (2) describe the energy system. Suppose we now wish to examine the carbon cycle as well. To do this we add a second block of equations describing the emissions and diffusion. If $\gamma(\ell\ell, i)$ is the emissions per unit activity x_{it} into stratum $\ell\ell$, emissions in a given period, $E(\ell\ell, t)$ are:

$$(3) \qquad E(\ell\ell, t) = \sum_{i=1}^{n} \gamma(\ell\ell, i) x_{it}, \qquad \ell\ell = 1, \ldots, L.$$

Next denote $M(\ell\ell, t)$ as the total mass of carbon in a given stratum at the end of period t and $D(i,j)$ as the transition probabilities of a unit mass moving from stratum i to stratum j. From the basic diffusion equations we have

$$(4) \qquad M(\ell\ell, t) = \sum_{i=1}^{L} D(i, \ell\ell) M(i, t-1) + E(\ell\ell, t), \; \ell\ell = 1, \ldots, L, \; t = 1, \ldots, T$$

Finally, we impose standards on the energy sector that the total mass in a given stratum should not exceed $St(\ell\ell)$:

$$(5) \qquad M(\ell\ell, t) \leqq St(\ell\ell), \text{ all t.}$$

To implement the controls, we add equation set (3), (4), and (5) to our original problem in (1) and (2) and solve the optimization problem.

III. Results

The first question to investigate is whether the carbon controls we have suggested are feasible. Any nonfossil fuel energy source (fission, fusion, solar, or geothermal) will be an option for meeting the carbon dioxide constraint since nonfossil fuels have no significant carbon dioxide emissions.

The second question refers to the quantities in the controlled and uncontrolled paths. Table 1 shows the calculated *U.S.* energy consumption and world carbon emissions along the uncontrolled and controlled paths. These show two surprising results. First, although the time path of emissions is severely constrained, the total energy consumption is not. In fact, in later periods (when the nonfossil fuel production becomes most significant), consumption is higher because of the lower thermal efficiency of nonfossil sources. Second, it is surprising that the effect of a carbon constraint on *current* energy consumption (and on the composition of consumption) is almost negligible; it is only in the later periods that an efficiently designed program leads to noticeable modifications of the energy system.

In an optimization framework, as in an economy, constraints have their costs in terms of the objectives of the optimization, and associated with each of the carbon constraints are shadow prices on emissions. The last row of Table 1 gives the shadow prices for carbon emissions in the control program. The prices per ton start very low ($.14 per ton carbon), become significant in the third period, and rise to a very high level of around $90 a ton (1975 prices) by the end of the next century. These should be compared with the prices per ton of carbon of carbon-based fuels, which are around $25 a ton for coal, $100 a ton for petroleum, and $200 a ton for natural gas.

We can also ask what the carbon dioxide constraints are costing *in toto*. Table 2 shows the discounted cost of each of the three control programs, calculated from the attained value of the objective function in (1). Clearly the control of carbon dioxide is a very expensive operation —the middle control path 3 has discounted costs of $87 billion in 1975 prices. As a corollary, it is evident that the social return to new "carbon control technologies"—the science fiction stories referred to earlier— would be very high if carbon dioxide were to be controlled.

It should also be noted that, since at the present the only proven large-scale and low-cost alternative to carbon-based fuels is nuclear fission, the outcome of the nuclear debate will significantly affect the prospects of carbon dioxide control. If nuclear fission were to be constrained along with carbon emissions, then, until major breakthroughs in alternative technologies become available, the growth rate of energy consumption would be effectively con-

TABLE 1—ENERGY CONSUMPTION, CARBON EMISSIONS, AND CARBON EMISSION TAXES

	1970 (Actual)	1980	2000	2020	2040	2100
Energy Consumption, United States, 10^{15} btu/yr						
Uncontrolled CO_2	71	76.	92.	155.	250	395.
100 percent increase CO_2		76.	92.	142.	160.	405.
Global Carbon Emissions, 10^9 tons/yr						
Uncontrolled CO_2	4.0	6.9	10.7	18.4	40.1	45.4
100 percent increase CO_2		6.9	10.7	16.6	16.0	4.9
Carbon Emission Tax ($/ton)						
Uncontrolled CO_2	.00	.00	.00	.00	.00	.00
100 percent increase CO_2		.14	1.02	8.04	67.90	87.15

Notes: Carbon emissions are tons of carbon dioxide, carbon weight, while carbon taxes are calculated dual variables in the efficient program, and have the dimension of 1975 dollars per ton carbon weight of emission. Source is Nordhaus (1976).

strained to zero. Preliminary estimates indicate that the cost of prohibiting nuclear power along with a limitation on carbon dioxide concentrations is around five times the most restricted case in Table 2.

In summary, an efficient program for meeting reasonable carbon dioxide standards appears feasible and, moreover, requires little change in the energy allocation for 20 to 40 years. Subject to the limitations of the techniques used here, we can be relatively optimistic about the technical feasibility of a carbon dioxide control strategy. The central question for economists, climatologists, and other scientists remains: How costly are the projected changes in (or the uncertainties about) the climate likely to be, and therefore to what level of control should we aspire? And for students of politics, the question is: How can we reasonably hope to negotiate an international control strategy among the several nations with widely divergent interests?

TABLE 2—COST OF CARBON DIOXIDE CONTROL PROGRAMS

	Path			
	1 Uncontrolled	2 200% Increase	3 100% Increase	4 50% Increase
Discounted Total Cost, Billions of 1975 Dollars	$0	$30	$87	$540
Discounted Total Cost as Percent of Discounted World *GNP*	0%	.06%	.12%	.81%

Source: Nordhaus 1976.

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