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ECONOMIC GROWTH AND CLIMATE:

THE CARBON DIOXIDE PROBLEM*

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ECONOMIC GROWTH AND CLIMATE:
THE CARBON DIOXIDE PROBLEM*

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.

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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. The important atmospheric characteristics for man's activities are temperature, precipitation, snow cover, winds and so forth. 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 0.6° C (see Figure 2 below). The disputes about the sources of such variations are reminiscent of business cycle theory--with theories mentioning everything from sunspots to quasi-periodic oscillations to the existence of many locally stable but globally unstable equilibria.

The overall observation of high amounts of "red noise"--as is also the case for typical economic time series--has important implications for those who are concerned with climatic implications of man's behavior. This implies that the climatic stability we generally assume should not be taken for granted; indeed, some have pointed out that the string of recent good harvests in the midwestern U. S. is no more likely than Dust Bowls of the 1930s. Moreover, given the slowly changing climatic patterns it is difficult to separate nature's red noise from the red signal associated with smoothly growing economic activity.

At what point is there likely to be a significant effect of man's activities on the climate? Many climatologists feel that the changes witnessed in the last century--the 0.6°C. range--have led to major, albeit not catastrophic events. It should be stressed that the changes in temperature are rather trivial. It is not the mean temperature change which is economically significant, but other variables such as degree-days, precipitation, and snow cover, and these tend to vary much <u>more</u> than global mean temperature. Examples of high amplification are changes in precipitation and changes in the latitude of monsoons with changes in temperature. (See Machta and Telegados [1974] or Schneider [1976].) Given the amplification, it seems prudent to consider a change of 0.5°C. as a significant change.

The inadvertent affects of man's activities on climate have been estimated using a variety of techniques. Although the estimates are uncertain, many authors place the date at which significant climatic change can occur as follows: For carbon dioxide such a change would come with about 20% increase in atmospheric concentrations. According to recent projections, we shall probably reach this level in the 1985-1990 period (see Broecker [1974]). For industrial heat (sometimes called "waste heat"), the estimates are less secure. Using the same methodology as for the carbon dioxide estimates, it is estimated that waste heat will lead to an increase of 0.5°C around 2080. For particulate matter, the matter is even more problematical because the <u>direction</u> of effect is uncertain. A rather mechanical exercise of projecting the growth of particulates at the rate of growth of energy consumption leads to the conclusion that particulates would have the significant 0.5° C effect by about 2030, but this procedure is extremely dubious. From these estimates, it appears that carbon dioxide will be the first industrial emission to affect climate on a global scale, with a "significant" effect appearing sometime in the next twenty years; for this reason we will focus only on carbon dioxide in the present report.

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 (Manabe and Wetherald [1975]) predicts that a doubling of atmospheric concentrations of carbon dioxide would lead to a global mean temperature increase of $3^{\circ}C$. The predicted temperature increase by latitude is shown in Figure 1, indicating that there is considerable amplification at high latitudes. In addition, in Figure 2 we have shown 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 of this paper. The significant point to note is that there are predicted to be vary large increases in temperature in the coming decades, taking the climate outside of any temperature pattern observed in the last 100,000 years.

Control strategies

The outcome just described is the effect of an uncontrolled economy-climate system, that is one in which the economy and the energy system evolve simply on the basis of economic forces, without considering the feedback of economic activity through climate back to man. 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.

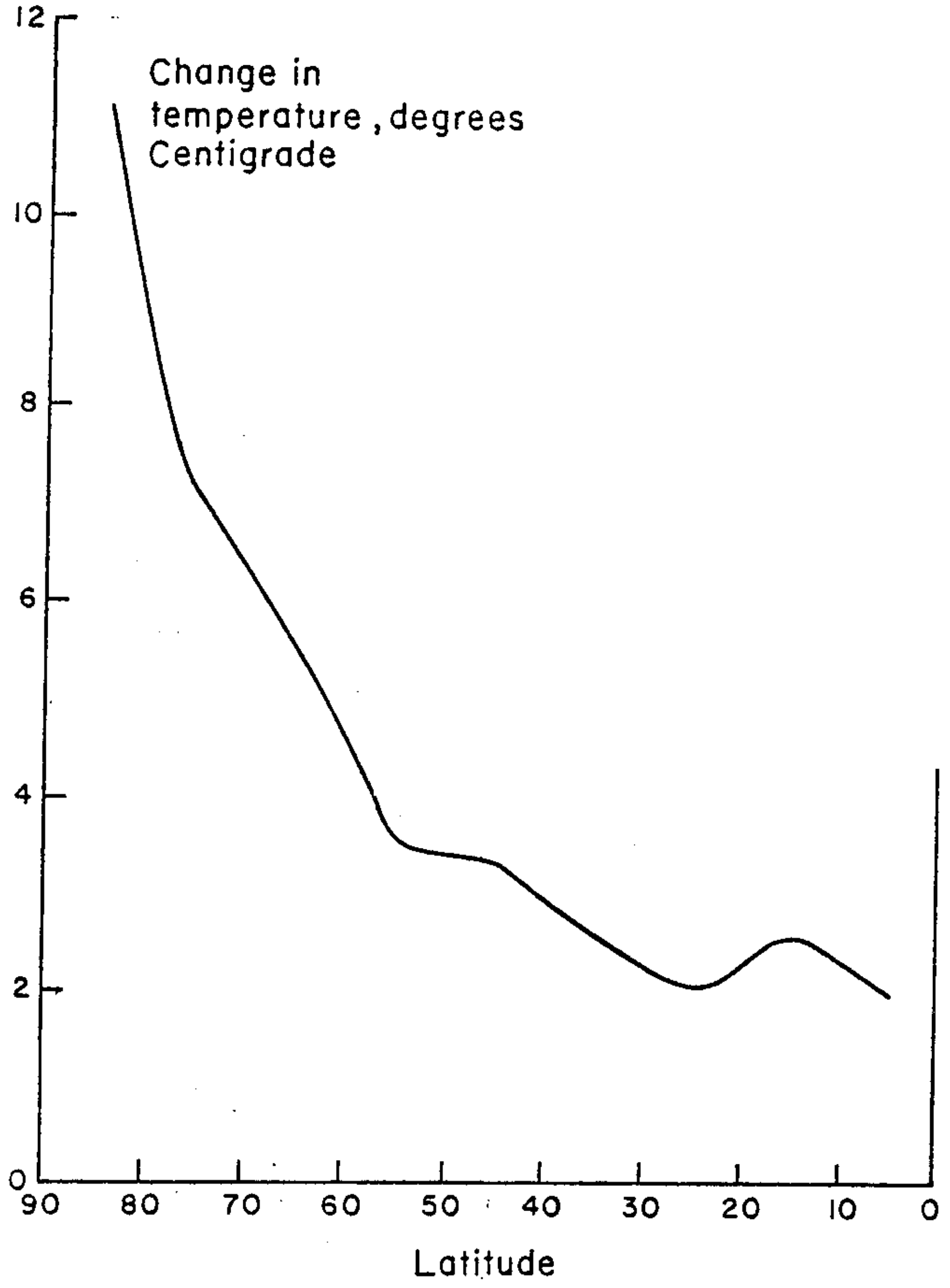


Figure 1. Estimated effect of doubling of atmospheric carbon dioxide on surface temperatures, by latitude. From Manabe and Wetherald [1975].

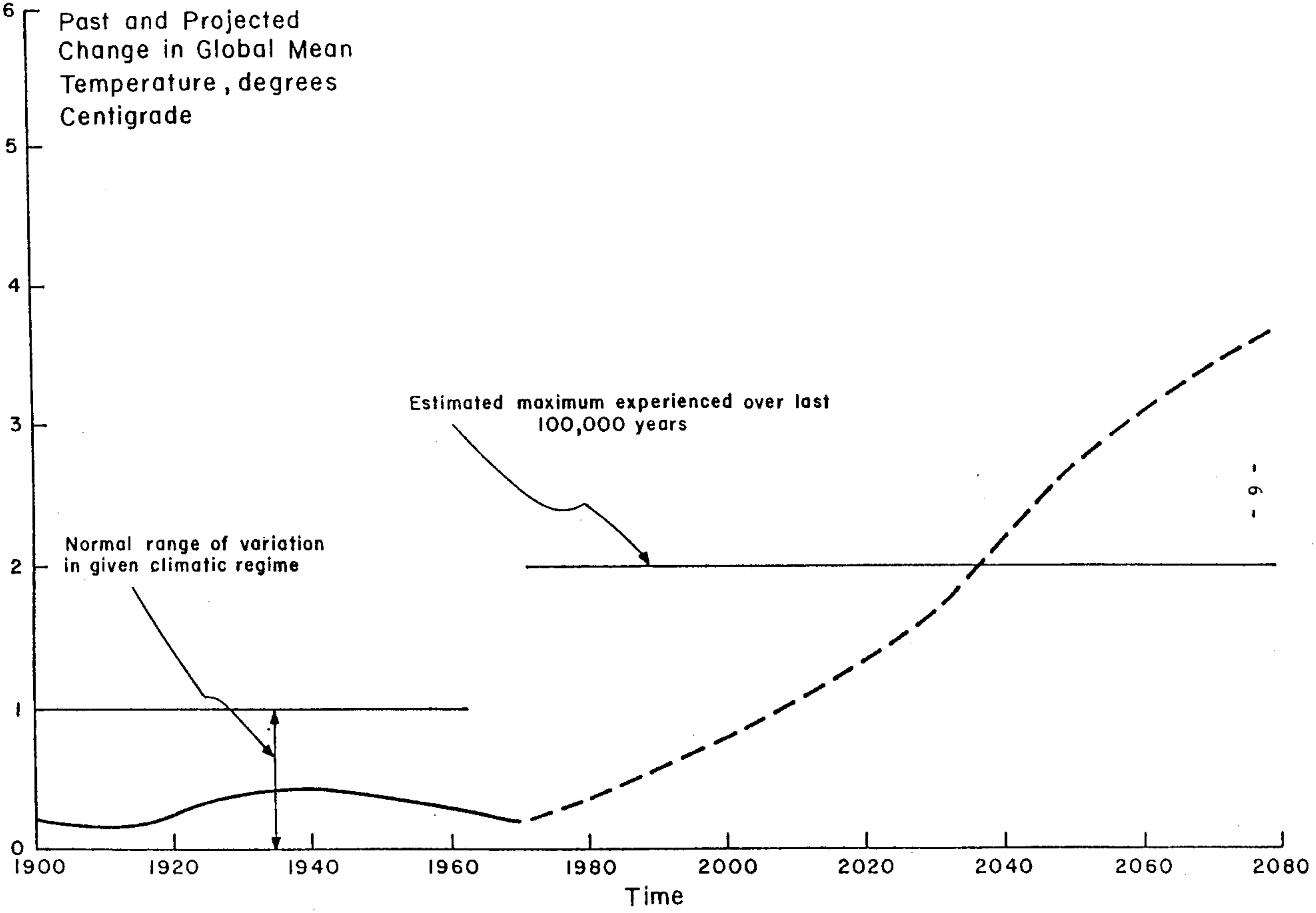


Figure 2. Past and projected global mean temperature, relative to 1880-84 mean. Figures up to 1970 are actual. Figures from 1970 on are projections using 1970 actual as a base and adding the estimated increase due to uncontrolled buildup of atmospheric carbon dioxide. Sources given in Nordhaus [1976].

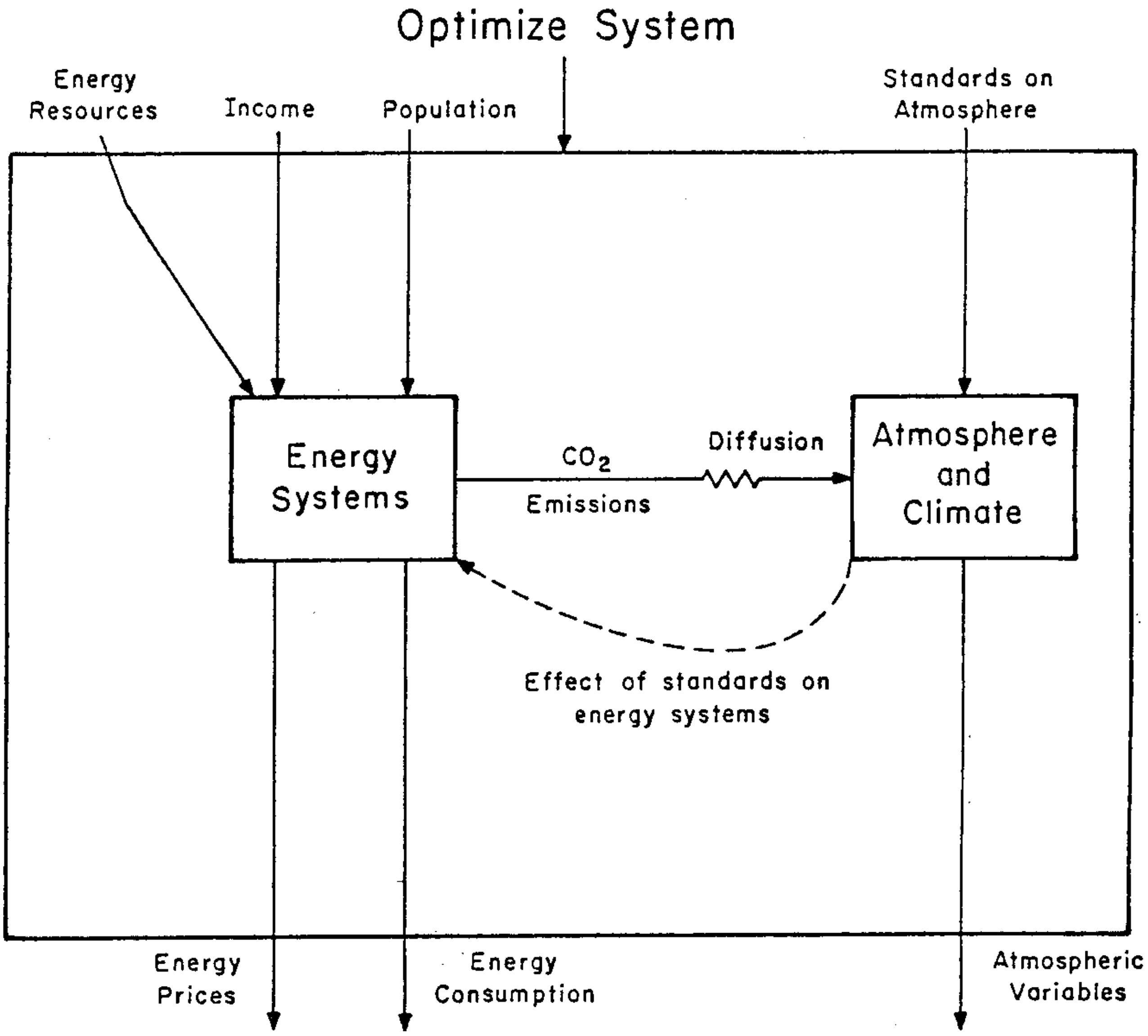
We therefore investigate strategies for control of atmospheric carbon dioxide. A control strategy involves two aspects: On a scientific and aggregate level, the feasibility of control techniques must be explored. But there must also be a way to decentralize the controls so that nations, producers, and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

Figure 3 gives an overview of the model used to investigate strategies. The block labelled "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 interaction of the supply and demand forces leads to a path of prices and consumption over time. To account for the externalities, such as the carbon dioxide cycle analyzed here, 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 right hand side of Figure 3. 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 three general approaches to the problem of keeping atmospheric concentrations to a reasonable level.

The first strategy, which is the route chosen in the present paper, is to reduce emissions of carbon dioxide. This takes place by substituting non-carbon-based fuels for carbon-based fuels. A second strategy is to offset the effects of emissions of carbon dioxide. This can take the form of introducing the carbon into places where it has delayed climatic effect (such as compressing and pumping liquid CO_2 into the deep oceans), or of using climatic engineering

Figure 3. Overview of Model Optimizing the Energy-Environment System



to offset the effects (such as painting roofs and roads white). A third approach would be to use natural or industrial processes to clean out the carbon dioxide from the atmosphere <u>ex post</u> (such as by growing and pickling trees). To avoid the odor of science fiction, we have limited control strategies to the first strategy--reductions in demand and substitution in supply.

The final question in the optimization concerns the "standards" imposed in Figure 3. 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. (Note that the increase is more than the "significant level" discussed above). According to most sources, the range of variation between distinct climatic regimes is in the order of 5°C, and at the present time the global climate is at the high end of this range. As shown in Figure 2, if global temperatures were more than about 2°C above the current value, this would take the climate outside of the range of observations which have been made over the hundred thousand years. Within a stable climatic regime, such as the current interglacial, a range of variation of 1°C is the normal variation.

Given the estimate of the effect of carbon dioxide, to keep the effect within the normal variation implies that 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. <u>It must be emphasized that the process of setting standards used in this report is deeply unsatisfactory, both from an empirical point of</u>

view and from a theoretical point of view. 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. In the real world, the policy can take the form either of taxing carbon emissions, or of physical controls (like rationing). In an efficient solution the two are interchangeable; in practice, the use of taxes is much simpler because the taxes tend to be much more uniform than the quantities. We therefore will concentrate on "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 [1953]) a market allocation can be described by the mathematical programming problem:

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

subject to resource constraints,

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

where A_{ij} is the content of scarce resource j per unit activity of good i , and $\overline{R}_j$ 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 (U. S. 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:

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

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

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

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

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

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.

Results

The first question to investigate is whether the carbon controls we have suggested are feasible. The question of feasibility rests on the exitence of activities which equilibrate supply and demand with relatively low levels of carbon dioxide emissions. In reality, any non-fossil fuel energy source (fission, fusion, solar, or geothermal) will be an option for meeting the carbon dioxide constraint since non-fossil fuels have no significant carbon dioxide emissions. In the program discussed above, we consider both solar and nuclear fission as an alternative to fossil fuels, but the results would be identical for any of the non-fossil fuels, with the same cost structure.

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 non-fossil fuel production becomes most significant), consumption is higher because of the lower thermal efficiency of non-fossil 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. The control program takes the form of imposing upper bounds on the level of atmospheric concentrations, and associated with each of the constraints are shadow prices on emissions. The last row of Table 1 gives the shadow prices for carbon emissions for the controlled program. The prices per ton start very low ($0.14 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,

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

	1970 (Actual)	1980	2000	2020	2040	2100
Energy Consumption, U.S., 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	0.00	0.00	0.00	0.00	0.00	0.00
100 percent increase CO_2		0.14	1.02	8.04	67.90	87.15

Notes: Energy consumption use the U. S. Bureau of Mines conventions on conversions. 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].

$100 a ton for petroleum, and $200 a ton for natural gas. Put differently, the current implicit subsidy on carbon fuels is less than one percent of the price, but without a control program, that subsidy will be growing very rapidly.

We can also ask what the carbon dioxide constraints are costing *in toto*. Whereas the shadow prices give the cost on the margin, we can examine the attained value of the objective function in (1) to determine the overall cost. Table 2 gives the calculation of the discounted cost of meeting the three different constraints. Clearly the control of carbon dioxide is a very expensive operation--the medium 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 effect 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 constrained 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.

We have investigated an efficient program for meeting certain carbon dioxide standards. These indicate that such programs appear feasible and,

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%	0.06%	0.12%	0.81%

Source: Nordhaus[1976]

moreover, require little change in the energy allocation for the first two 20-year periods, and only in the third period, starting around 2010, do significant modifications in the allocation take place. The modifications take the form of reducing fossil fuel use in the non-electric sector, and replacing it with non-fossil fuels. The efficient programs analyzed here eventually have very high implicit taxes on carbon emissions and therefore on carbon-based fuels; the effect on energy prices (not presented here) or on total real income (presented in Table 2) are expensive but not unthinkable.

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 sould 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?

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