International Institute for
Applied Systems Analysis
IIASA www.iiasa.ac.at

# Can We Control Carbon Dioxide?

Nordhaus, W.D.

IIASA Working Paper

WP-75-063

June 1975

Nordhaus, W.D. (1975) Can We Control Carbon Dioxide? IIASA Working Paper. WP-75-063 Copyright © 1975 by the author(s). http://pure.iiasa.ac.at/365/

# CAN WE CONTROL CARBON DIOXIDE?

William D. Nordhaus

June 1975

WP-75-63

# Can We Control Carbon Dioxide?

by William D.Nordhaus *

## I. Introduction

In recent years, the concern about the tradeoffs between economic growth and environmental quality have been paramount. To a large extent, the energy sector has been the locus of the major battles. For the most part, the concerns have been with local environmental problems such as disputes over air and water quality, nuclear accidents, and radioactive wastes. Although these problems have not been solved, it appears that as a result of considerable technical work that techniques exist (even if political will does not) to reduce most local environmental problems to a tolerable level.

There remain on the agenda, however, a number of global environmental problems, and again these relate mainly to the energy sector. In particular, it appears that emissions of carbon dioxide, particulate matter, and waste heat may, at some time in the future, lead to significant climatic modifications. Of these, it appears that carbon dioxide will probably be the first man-made emission to affect climate on a global scale, with a significant temperature increase by the end of the century.

---

* This work was performed with the support of the United States National Science Foundation and the International Institute for Applied Systems Analysis, Laxenburg, Austria. Discussions with Cesare Marchetti and Alan Murphy helped me find my way in the climatic literature; Leo Schrattenholzer skillfully programmed the model; and Mrs.Lilo Roggenland patiently typed the manuscript. None of the above are responsible for errors or opinions expressed in the paper.

A brief overview of the problem is as follows: combustion of fossil fuels leads to significant emissions of carbon dioxide into the atmosphere. The emissions slowly distribute themselves by natural processes into the oceans, into the biosphere, and, at a very slow rate, into fossils. Although this process is not completely understood, it is clear that the residence time of carbon dioxide in the atmosphere is extremely long, and that at the present approximately half of the industrial carbon dioxide remains in the atmosphere. The ultimate distribution of carbon dioxide between the atmosphere and the other sinks is not known, but estimates of the manmade or industrial carbon dioxide asymtotically remaining in the atmosphere range between about ten and fifty percent.[1]

The effects of the atmospheric buildup of carbon dioxide are not known with certainty, but there are thought to be two general effects. The first, and most highly publicized, is the effect on the climate through the greenhouse effect. Because of the selective filtering of radiation, the increased carbon dioxide is thought to lead to an increase in the surface temperature of the planet. Recent estimates range from 0.6°C. to 2.4°C. for the mean temperature increase due to a doubling of the atmospheric concentration. (See Sellers (1974), Table 2 for a recent tabulation). Recent experiments indicate, however, that the sensitivity of the temperature is much greater in the polar regions than in the lower latitudes.[2]

---

[1] See Matthews et al. [1971], Machta [1972], Keeling [1973], NCAR[1974].

[2] See Sellers [1974], p.832 and NCAR [1974] , p.16.

Simple models used by Budyko (see [1974a] and [1974b] ) lead to rather dramatic conclusions about the long-run effects of the carbon dioxide buildup, with a rapid disappearance of the ocean-borne ice and gradual melting of the land-based ice. The latter is spread over a period of a few thousands of years, while the former is predicted by Budyko to occur in a period as short as a decade. Other models do not lead to such dramatic effects, in part because they do not include the full temperature-ice-albedo feedback mechanism.

The purpose of the present paper is not to spell out the possibilities for climatic change; this has been done elsewhere in great detail. It should be stated what appear to be the current estimates of uncontrolled carbon dioxide buildup and the estimated response to it. According to the model used here, uncontrolled paths will lead to significant increases in average temperature within the next fifty years, with increases in temperatures in high latitudes about five times the mean.[1] The major sensitive point in the short run is the floating Arctic ice. With summer temperature anomalies of 4°C., the summer ice is predicted by Budyko to disappear in four years (see Budyko (1974b),p.277). According to most studies, an open Arctic ocean would lead to a dramatic change in the precipitation patterns, as well as the temperature patterns, with the most important changes occurring in the high latitudes of the Northern hemisphere (see Gates (1975)).

---

[1] See Sellers [1974], NCAR [1974], and results cited by Flohn at IIASA Workshop.

Aside from this rather sharp and immediate result, the other effects of increased concentrations are either less discontinuous or act much more slowly. Budyko (1974a) argues that a fifty percent increase in carbon dioxide would lead to melting of the land-borne ice, raising the level of the oceans up to 80 meters and dramatically warming the global temperature--the eventual warming being in the order of $5^{o}C$. when all the feedback effects have taken place. This results is almost certain to be extremely slow, spread over a period of around 5000 years, so that its possibility should probably be heavily discounted.

The consequences of these changes for human affairs are clouded in uncertainty. It is unlikely that any dramatic, global changes will be forthcoming before the end of the century--dramatic changes such as changes in sea level will be much slower to appear (see Lamb [1972], pp.34). On the other hand, it is possible that a large redistribution of precipitation will occur within a relatively short period.

The second major effect of increased atmospheric concentration of carbon dioxide would be the direct effect on agriculture. Since increased carbon dioxide can lead directly to higher rates of photosynthesis, there can be beneficial effects on agricultural production within quite a short period of time.

An overview of the cycle can be seen in Figure 1. There are five sets of state variables: (I) the activities of sources; (II) the initial sinks for the carbon dioxide emissions; (III) the ultimate sinks for the emissions; (IV) the level of proximate effects of the increased output of carbon dioxide; and (V) the ultimate effects on man and other important variables.

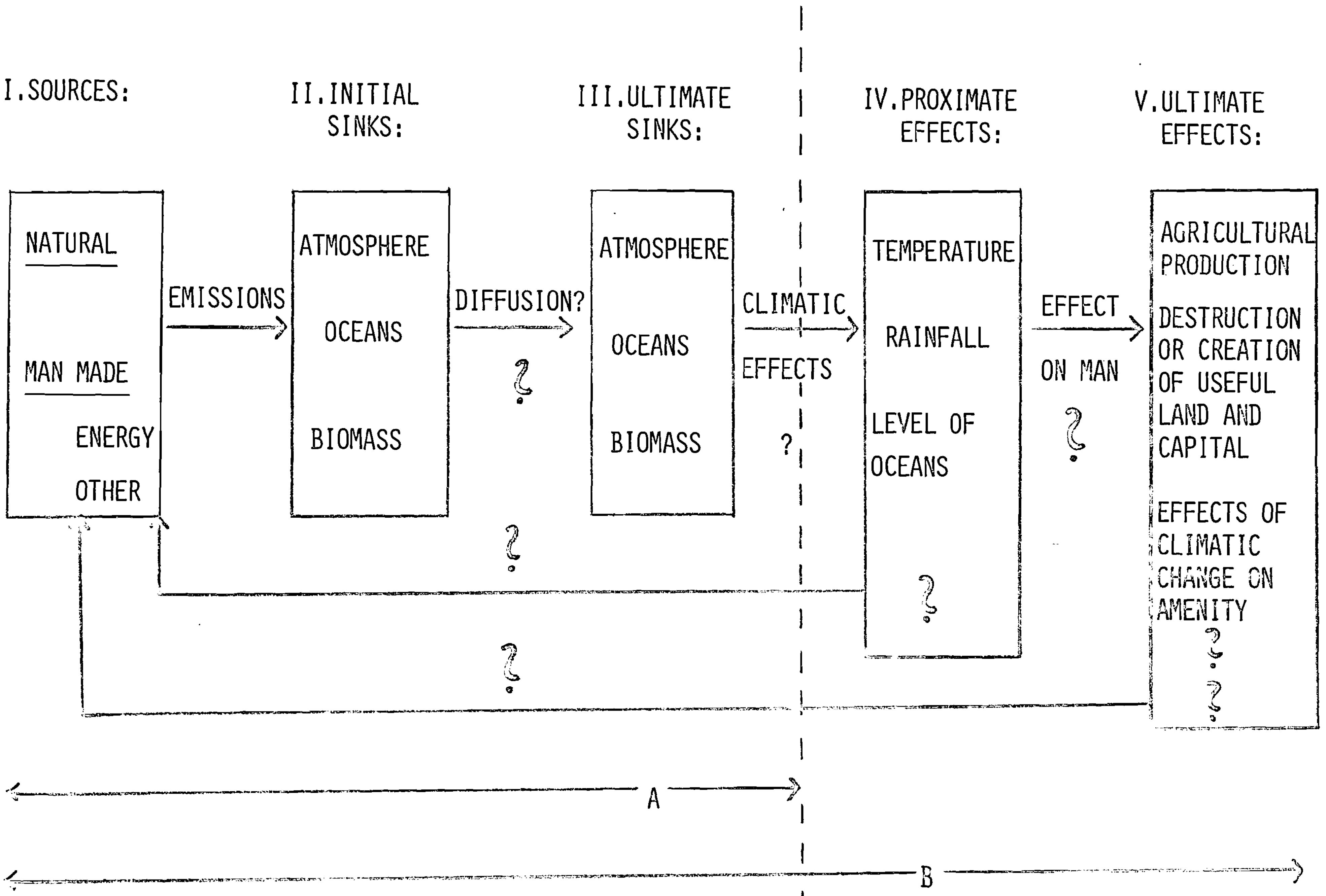

FIGURE 1. <u>THE CARBON-DIOXIDE CYCLE</u>

Relating to the different state variables are four functional relationships: (1) the emission equations relating the emissions of carbon dioxide to the activity levels of the sources; (2) the diffusion equations indicating how the initial distribution of carbon dioxide is distributed in the various ultimate sinks; (3) the climatic effects, indicating how the important climatic variables are related to the levels of carbon dioxide in the different sinks; and (4) finally the relation of different climatic variables upon the important variables for man.

The major uncertainties in determining the cycle are indicated by the placement and size of the question marks in Figure 1. Roughly speaking, the further down the cycle, the larger the uncertainties about the functional relations; also, the larger are the uncertainties about what variables will be affected, especially in the effects listed in categories III, IV and V.

The linkage from energy to climate and man just described can be seen as the effects of an uncontrolled development--that is one in which the energy system and emissions of carbon dioxide evolve simply on the basis of economic forces and without taking into account the feedback of carbon dioxide onto climate and man. Put differently, the externalities of carbon dioxide are ignored. If this path is unacceptable--for reasons discussed above--then we must consider the alternatives. Table 1 gives a list of four approaches to the control problem.

There are four general approaches to the problem of keeping atmospheric concentrations to a reasonable level. At the bottom of the list (in desirability if not likelihood) is the approach of doing nothing. This simply consists of letting the market

## TABLE 1. CONTROL STRATEGIES

1. REDUCE EMISSIONS:
    - A. REDUCE DEMAND*
    - B. SUBSTITUTION IN SUPPLY*

2. NEGATE DAMAGES
    - A. MIX INTO OCEANS
    - B. OTHER OFFSETTING EFFECTS (PARTICULATES, PAINT, BAND-AIDS)

3. CLEAN UP EX-POST
    - A. REMOVE FROM AIR
    - B. GROW TREES

4. NATURES WAY AND PRAY

    DO NOTHING (RULED OUT)

*CONSIDERED IN MODEL

forces dictate the solution (with the price of climatic change and disruption set implicitly at zero). The other three strategies rely on the fact that the negative effects probably are related to the atmospheric concentrations of carbon dioxide, while the desideratum is energy consumption, and that there is no iron law linking the two variables together in an inexorable relation.

The first strategy, which is the route chosen in the present paper, is to reduce emissions of carbon dioxide. This can take the form of reducing usable energy consumption or of substituting non-carbon based fuels for carbon-based fuels.

The second strategy is to negate the damages of emissions of carbondioxide. This can take the form of introducing the carbon into places where it does less damage (such as the deep oceans), or of using counteracting forces to offset the effects (this would be such factors as using stratospheric dust to cool the earth, changing the albedo by putting gauze over the arctic,(or by painting roads or roofs white or by other means). The second approach, then, relies on the inhomogeneities in nature to minimize the impact without influencing the actual emissions.

A third approach would be to use other processes to clean out the carbon dioxide from the atmosphere ex post. This approach would rely on the possibility that removing the carbon from the air by a natural or industrial process is cheaper than refraining from putting the carbon in the atmosphere in the first place. Two possibilities here are simply growing trees and locking the carbon in the trees, or removing the carbon from the air by an industrial process.[1]

---

[1] Many of the technological ideas mentioned above were developed in conjunction with C.Marchetti.

With this overview of the problem and solution of the carbon dioxide buildup, a few general comments are useful. First, there is great uncertainty as to the exact description of the carbon dioxide cycle. Particularly further down the cycle shown in Figure 1, the greater are the difficulties of estimating the tradeoffs. The second point, however, is that a significant problem or at least significant changes may appear in the future. Third, as shown in Table 1, there are many possible policy alternatives for control of carbon dioxide. Finally it should be emphasized that there are no market or political mechanisms which ensure that the appropriate policy for control will be chosen.

In what follows we analyze a very limited problem: how can we limit the concentration of atmospheric carbon dioxide to a reasonable level? And how much would a control path cost if it were implemented on an efficient basis?

In the present report, we consider the sequence only as far as the arrow A in Figure 1 indicates; this part of the cycle is relatively well understood, and we therefore are dealing with relatively minor levels of uncertainty.

It is hoped that progress can be made on the more difficult and important question involved with the incorporation of the rest of the cycle, shown as B in Figure 1.

Because we cannot include the complete cycle at the present time, we must confine ourselves to a simple and unsatisfactory way of setting controls. Thus, in the present paper we describe the technological aspects of the model, and estimate the optimal response to arbitrary standards, as well as the differences between controlled and uncontrolled programs. It is hoped that in a future report, the methodological and empirical steps necessary for setting optimal standards, as well as questions of implementation, will be treated, but these are outside the scope of the present paper.

One final disclaimer is necessary. We are analyzing the effects of carbon dioxide under the assumption that no other variables are changing. It may well be, however, that other variables--such as atmospheric dust or waste heat--will either reinforce or counteract the effects of carbon dioxide. If this is the case, the conclusions could be quite different. On the other hand, once a model similar to that presented here for carbon dioxide is worked out for the other variables, the task of evaluating the overall optimum is straightforward.

# II. Dynamics of the Carbon Dioxide Cycle

## 1. Genesis of Carbon Dioxide

Keeling has recently described quite carefully the origins of man-made carbon dioxide[1]. Approximately 98 percent of man-made carbon dioxide originates in the energy sector, although of this about 5 percent end up in non-energy uses (in asphalt, bitumen, lubricants etc.). The other two percent of the man-made source is cement production. Table 2 gives the conversion factors for deriving the emissions of carbon dioxide from the consumption of fossil fuels, as well as the assumed conversion factors for non-fossil technologies.

The balance of production of natural carbon dioxide is more complicated and will be discussed in the next section.

---

[1] Keeling [1973].

Table 2. Emission Factors for Carbon Dioxide

| | Carbon fraction in fuel by weight | Fraction of fuel oxidized | Conversion factor (tons carbon per ton fuel) | Carbon content ($10^9$tons carbon per $10^{15}$btu) |
|---|---|---|---|---|
| Coal and lignite | 0.70 | 0.99 | 0.693 | 0.0279 |
| Crude Petroleum | 0.84 | 0.915 | 0.769 | 0.0239 |
| Natural gas | n.a. | 0.97 | n.a. | 0.0144 |
| Electrolytic Hydrogen | 0 | n.a. | 0 | 0 |
| Nuclear energy | 0 | n.a. | 0 | 0 |
| Solar | 0 | n.a. | 0 | 0 |

Source: For fossil fuels, from Charles D.Keeling [1973], p.191, 180, 181, 178. The conversion factors (from Keeling) are 12,400 btu $lb^{-1}$ for coal and lignite, 19,000 btu $lb^{-1}$ for petroleum, and 1,030 btu $ft^{-3}$ for natural gas.

n.a. = not applicable.

Note: For nuclear fuels and electrolytic hydrogen, it is assumed that the capital equipment is produced without cement or fossil fuels. If this assumption were incorrect, the figure would be a small fraction (one twentieth to one thousandth) of the figures for fossil fuels. Also, note that synthetic fuels (liquefied and gasified coal) are charged for the full carbon content of the original fuel since the carbon losses are airborne. Finally, it is assumed that the hydrogen fuels used for transportation are not converted to hydrocarbon fuels (as for example in methanol).

## 2. Diffusion of Atmospheric Carbon Dioxide

Once emissions of carbon dioxide enter the atmosphere, the process of diffusion and disposition into the ultimate sinks begins. Compared with most atmospheric pollutants, this process is extremely slow. Thus according to Keeling [1973], man's activities have added 17.9% to the atmospheric carbon dioxide over the period 1860 to 1969; of this approximately 10%, or 65% of the total added, remains in the atmosphere (see Machta [1972]). An obvious but unanswered question is where the rest of the carbon dioxide has gone, and whether the division between atmosphere and other sinks will continue to be in the same proportion in the future as in the past.

According to early estimates, roughly half the man-made carbon dioxide was remaining in the atmosphere (see PSAC [1965], Matthews et al. [1971]). Recently, the work of Machta and his associates has led to more refined models of the diffusion process, models which lead to rather different conclusions as far as the long term distribution of carbon dioxide. In what follows we will use the results of Machta as presented in Machta [1972].

The basic physical processes representing the diffusion of the emissions of carbon dioxide are simple first order kinetics. In the original model of Machta, first order kinetics are assumed to hold between two layers of the atmosphere--troposphere and atmosphere--as well as between the atmosphere and the mixed layer oceans, and between the mixed and the deep layer of the oceans. The first order kinetics laws assume that a fixed fraction of the contents of one reservoir transfers to another reservoir per period. This implies that the equilibrium content of each reservoir is a linear function of the total mass in all reservoirs.

In the original Machta model, it was assumed that a second process relates the exchange between the atmosphere and oceans and the biosphere via primary productions or gross photosynthesis (PS). More specifically, Machta assumed that a mass of carbon equal to PS is transferred from a reservoir to biosphere every year; that after a specified number of years the carbon simply returns to the reservoir by the process of decay. This assumption has been slightly modified in what follows by assuming that the process of decay is exponential rather than "one-hoss-shay", but with the same mean residence time. This assumption simply changes the entire dynamic structure into a first-order Markov process rather than a mixed Markov-fixed lag system.

The basic structure has been laid out in Figure 2. There are seven reservoirs in the model: two atmospheric strata (stratosphere and troposphere); two ocean layers (mixed ocean--down to 60 meters --and deep layer); and three biospheres (short-term land biosphere, long-term land biosphere, and marine biosphere).

In estimating the flow coefficients in Figure 2, all but two of the coefficients are determined in advance. The two co-

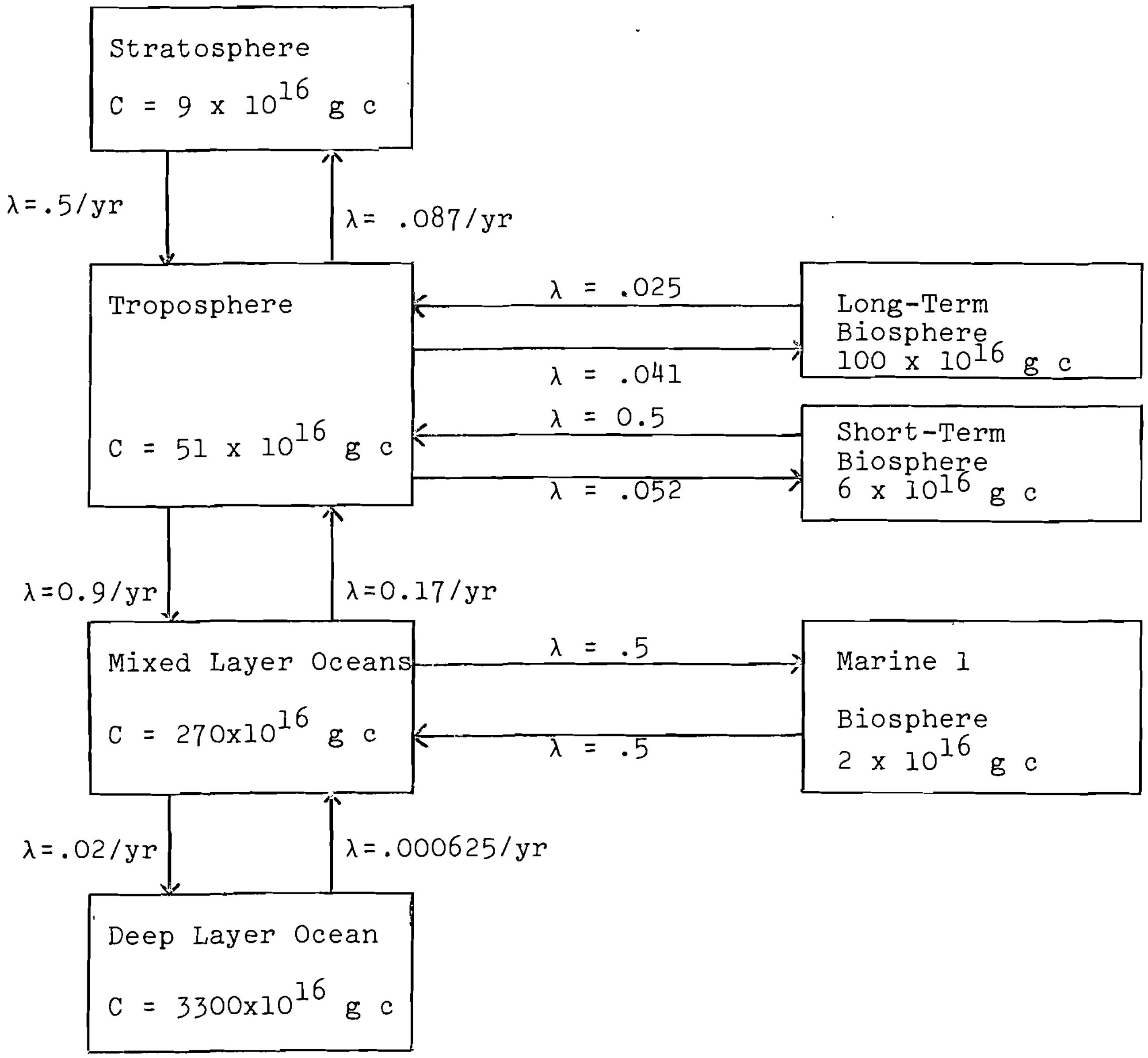

Figure 2. The first order transfer process between the seven reservoirs of carbon dioxide. The λ are the transfer coefficients, indicating what fraction of the mass of one reservoir is transfered to the second reservoir per year.

efficients relating to the transfer between the troposphere and the mixed layer, however, are estimated by Machta using residence times from bomb-$C^{14}$; according to his results (see his Table 2), the coefficients are relatively well-determined.

Three further points are worth mentioning. First, the estimates of the lags and levels of the biomass are due to the ecologists Woodwell, Olson, and Leith, according to Machta [1972]. The difficulty, however, is to estimate the effect of increased carbon dioxide concentrations on the rate of photosynthesis. Several authors suggest that for carbon dioxide limited biomass, the increase of photosynthesis will be 5% for each 10% increase in carbon dioxide.

Woodwell and Olson estimate that very roughly half of the land biosphere is carbon dioxide limited, so that an increase of 10% in atmospheric carbon dioxide is assumed to lead to an increase of 2.5% in gross photosynthesis. These estimates are highly uncertain, appear high to the present author, and are questionable in light of other studies, but they will be retained for the present paper.

A second factor is the problem of buffering of the carbon molecules in the sea. Machta writes as follows (p.126):

> [Consider] the dependence of the partial pressure of carbon dioxide on other carbon molecules in the sea. Thus the fractional change in the carbon dioxide pressure is ten times greater than the fractional change in the inorganic carbon content of the mixed layer. This buffering effect has the following consequences: Assume for the sake of explanation that the mixed layer has a carbon content equal to that of the atmosphere and that the mixed layer does not exchange with the deep ocean. Then if 11 units of carbon dioxide are added to the atmosphere, the equilibrium partition between air and mixed layer will not be 5.5 in air and 5.5 in ocean but rather 10 in

> air and only 1 in oceans. This 10 to 1 ratio may, according to Keeling, be as low as 6 to 1 or as high as 14 to 1.

The effect of the buffering factor, b, is that the "effective mass" of organic carbon is b times greater in the oceans than in the atmosphere; consequently the ratio of the exchange coefficients must be multiplied by b.[1]

It should be noted that the reservoir of fossilization has been omitted from the model; this is simply because the rate of fossilization is four orders of magnitude less than the rate of photosynthesis. According to Johnson (Singer [1971], p.8), the rate of fossilization is $10^{13}$ grams carbon/yr, which is approximately one part per 100,000 of the biomass. This rate is too small to effect the results within the time frame we are considering.

The technical operation of the model can be easily shown. Let $d_{ij}$ be the transfer coefficient per year from reservoir i to reservoir j; let the one-year transfer matrix $[d_{ij}]$ be represented by D. Note that D is a Markov matrix, so $\sum_{j=1}^{7} d_{ij} = 1$.

---

[1] The Machta model contains one small technical error in that it simply multiplies the coefficient $\lambda_{M\to T}$ (the transfer from the mixed layer to the troposphere) by b, resulting in some cases of a coefficient greater than unity. In our interpretation, we set the coefficient $\lambda_{T\to M}$ at 0.9, and then $\lambda_{T\to M}$ is equal to .9x270/51 b. There is one further puzzle in the Machta discussion: He states that the different behavior of $C^{12}O_2$ and $C^{14}O_2$ lies in the buffering action of the ocean for $C^{12}O_2$ while $C^{14}O_2$, being present in trace quantities, exerts no buffering effect (p.130). Unless the buffering reaction is non-linear (not assumed in the Machta model) it is easily seen that the buffering effect is independent of concentrations and should therefore also operate on $C^{14}O_2$.

Further, let the mass of a given reservoir in year t be denoted by $M_i(t)$, i=1,...,7; with the column vector M(t).

Our basic diffusion equation is that:

$$M_i(t) = \sum_{j=1}^{7} d_{ji} M_j(t-1) \quad ,$$

or in matrix form

$$M(t) = D' M(t-1)$$

where D' is the transpose of D.

Table 3 shows the one-year transfer matrix, the twenty-five year transfer matrix, and the asymptotic distribution $D^*=D^{\infty}$. Note that with a buffering factor of b = 10, the fraction of carbon dioxide remaining in the atmosphere after one year is 71 percent; for 25 years, the figure is 40 percent. This figure is slightly higher than other numbers (see Machta [1972], PSAC [1965], Keeling [1973]), but it should be noted that these are <u>marginal</u> residences for a twenty five years period whereas other figures cited refer to the average residence time of <u>all</u> man-made carbon dioxide. Note further that the asymptotic fraction of the total carbon dioxide remaining in the atmosphere is 11 percent, a figure well below the usual assumption in simple calculations.

Table 3A. One year distribution matrix, b=10

$$\begin{array}{c|ccccccc|}
 & T & S & M & D & SB & LB & MB \\
\hline
T & .71 & .087 & .11 & - & .052 & .041 & - \\
S & .50 & .50 & - & - & - & - & - \\
M & .09 & - & .072 & .02 & - & - & .008 \\
D & - & - & .000625 & .999375 & - & - & - \\
SB & .50 & - & - & - & .50 & - & - \\
LB & .025 & - & - & - & - & .975 & - \\
MB & - & - & .50 & - & - & - & .50 \\
\hline
\end{array}$$

Notes on matrix: The distribution matrix is a probability matrix whose rows each sum to one. The entries indicate the fraction of the mass of that basis on the left hand column which flows per unit time period to the basis on the top row. The basins are denoted as follows:

T = Troposphere
S = Stratosphere
M = Mixed layer of the Oceans (0 to 60 meters)
D = Deep Layer of the Oceans (Deeper than 60 meters)
SB = Short-term biosphere
LB = Long-term biosphere
MB = Marine Biosphere

Table 3B. Twenty-five year distribution matrix, b=10

$$\begin{array}{c|ccccccc|}
 & T & S & M & D & SB & LB & MB \\
T & .405 & .072 & .049 & .030 & .043 & .400 & .001 \\
S & .417 & .075 & .050 & .028 & .045 & .384 & .001 \\
M & .402 & .072 & .048 & .050 & .043 & .383 & .001 \\
D & .008 & .001 & .002 & .985 & .001 & .003 & .000 \\
SB & .417 & .075 & .050 & .029 & .045 & .384 & .001 \\
LB & .243 & .041 & .028 & .008 & .024 & .655 & .000 \\
MB & .414 & .074 & .050 & .048 & .045 & .367 & .001
\end{array}$$

Notes on matrix: The distribution matrix is a probability matrix whose rows each sum to one. The entries indicate the fraction of the mass of that basis on the left hand column which flows per unit time period to the basis on the top row. The basins are denoted as follows:

T = Troposphere

S = Stratosphere

M = Mixed layer of the Oceans (0 to 60 meters)

D = Deep Layer of the Oceans (Deeper than 60 meters)

SB = Short-term biosphere

LB = Long-term biosphere

MB = Marine Biosphere

Table 3C. Asymptotic distribution matrix, b=10

$$\begin{array}{c|ccccccc|}
 & T & S & M & D & SB & LB & MB \\
\hline
T & .097 & .017 & .051 & .629 & .011 & .190 & .004 \\
S & .097 & .017 & .051 & .629 & .011 & .190 & .004 \\
M & .097 & .017 & .051 & .629 & .011 & .190 & .004 \\
D & .097 & .017 & .051 & .629 & .011 & .190 & .004 \\
SB & .097 & .017 & .051 & .629 & .011 & .190 & .004 \\
LB & .097 & .017 & .051 & .629 & .011 & .190 & .004 \\
MB & .097 & .017 & .051 & .629 & .011 & .190 & .004
\end{array}$$

Notes on matrix: The distribution matrix is a probability matrix whose rows each sum to one. The entries indicate the fraction of the mass of that basis on the left hand column which flows per unit time period to the basis on the top row. The basins are denoted as follows:

T = Troposphere
S = Stratosphere
M = Mixed layer of the Oceans (0 to 60 meters)
D = Deep Layer of the Oceans (Deeper than 60 meters)
SB = Short-term biosphere
LB = Long-term biosphere
MB = Marine Biosphere

## III. Limits on Carbon Dioxide Concentrations

In the present report, we do not attempt to examine terribly carefully the question of appropriate standards; this must be deferred for future work. Rather, we attempt in the current report to examine the response of the system to arbitrarily given standards.

Unfortunately, it is difficult to consider what an appropriate set of standards might be. First, although considerable concern has been expressed about future trends in carbon dioxide concentration, the author knows of no attempts to suggest what might be reasonable standards, or limits to set in a planning framework. Second, it is clear that, except in the most extreme cases, standards cannot be determined *in vacuo*; rather they must be determined within a general framework of society's preferences and the technology.

In brief, the considerations for standards are as follows: The emissions of carbon dioxide in themselves are insignificant: carbon dioxide is not toxic to man until concentrations in the order of 20,000 parts per million (ppm) are reached, compared to current atmospheric concentrations of around 330ppm. Thus the effect of carbon dioxide on man occurs predominantly through modifications of climate and ecology.

As a first approximation, 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. According to most sources the range of variation between climatic is in the order of ± $5^{o}$C., and at the present time the global climate is at the high end of this range. If there were global temperatures more than 2 or $3^{o}$C. above the current average temperature, this would take the climate outside of the range of observations which have been made over the last several hundred thousand years. Within a stable climatic regime, the range of variation of ± $1^{o}$C. is the normal variation: thus in the last 100 years a range of mean temperature has been $0.7^{o}$C. On the other hand, studies of the effects of carbon dioxide on global temperature indicate that a doubling in concentration would probably lead to an increase in surface temperature of between 0.6 and $2.4^{o}$C. (see p.2 above).[1]

As a first approximation, we assume that a doubling of the atmospheric concentration of carbon dioxide is a reasonable standard to impose at the present stage of knowledge. First, according to the estimates of the effect on temperature, these temperature changes would be somewhere between the change observed over the last century and up to perhaps four times this variation. Although we do not know exactly what the effect is, we are probably not changing the climate more than has been associated with the normal random variations of the last few thousand years. Second, note that the effects will be temporary, not permanent, in that after the use of fossil fuels ceases the concentration will decrease over time as mixing of the atmospheric carbon into the ocean takes place; roughly speaking, the asymptotic level of carbon dioxide will be about one-fourth of the maximum concentration. Finally, it must be emphasized that the emissions

---

[1] For sources of the observations in this paragraph, see Lamb[1972].

are not irreversible. It is possible to remove carbon dioxide from the atmosphere by running combustion in reverse; thus if it appears that we have underestimated the magnitude of the effects of carbon dioxide, it is possible to engage in efforts to reduce the concentrations, or at least to offset the effects of the increased concentrations.

Thus as a first approximation to the setting of standards, we assume that doubling of atmospheric concentration of carbon dioxide is a reasonable upper limit. We will also test the sensitivity of our results to limits by imposing limits of fifty percent and two hundred percent increase. Table 4 shows the cases examined in the standards model.

The standards proposed here, as well as the reasoning behind it, are extremely tentative. It must be emphasized that the process of setting standards used in this section is deeply unsatisfactory, both from an empirical point of view and from a theoretical point of view. We can only justify the standards set here as rough guesses; we are not certain that we have even judged the direction of the desired movement in carbon dioxide correctly, to say nothing of the quantitative levels.

Table 4. Cases examined in standards model

| Case | Standard: Limit on atmospheric carbon dioxide, as percent of original concentration |
|---|---|
| I. Uncontrolled case | No limits (e.g. infinite) |
| II. Control Case A | Limited to 300 percent of original concentration |
| III. Control Case B | Limited to 200 percent of original concentration |
| IV. Control Case C | Limited to 150 percent of original concentration |

## IV. The Energy Model

The energy model used for the investigation is fully described elsewhere and only a brief sketch will be given here.[1] The energy model is a linear programming model designed to simulate the functioning of a competitive market for energy products. The basic building blocks of the model are the preference functions and the technology.

1. The preference function is drawn from market demand data. The energy sector is divided into four sectors (electricity, industry, residential, and transportation); and each of the four sectors has separate estimates for the market demand curves. These curves are functions of population, per capita income, and relative prices. Note that the demand functions are sensitive to the price of energy products.

2. The technology or constraint set is derived from engineering and geological data on the different resources available, and the costs of extraction, transportation, and conversion. Under the assumption that the economy is directed either by central planners who efficiently allocate resources, or is organized into competitive firms supplying the various goods and services, the technology can then be translated into the usual competitive supply curves for different products.

---

[1] For a description of an early version of the model, see Nordhaus [1973]. A more recent version, with minor changes in the model structure, will be forthcoming.

The procedure then involves maximizing the preference function subject to the technology constraints. This problem is solved by a medium-sized linear programming algorithm, involving 216 constraints and 1860 activities. The output of the solution is given in terms of the activity levels (e.g. the production of coal or oil in a given period), as well as the value of the dual variables (to be interpreted as shadow prices,opportunity costs, or, in a competitive framework, as the simulation of competitive prices).

Formally, the problem can be written as follows. We suppress time subscripts where unnecessary. Let $U_i$ be the marginal utility of good i and $c_i$ be the cost of good i. Then we desire to maximize the preference function:

$$(1) \quad \underset{\{x_i\}}{\text{maximize}} \quad \sum_{i=1}^{n} (U_i - c_i)\, x_i$$

This is subject to resource constraints:

$$(2) \quad \sum_{i=1}^{n} A_{ij}\, x_i \leqq \bar{R}_j \qquad j=1,\ldots,m$$

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.

The goods $x_i$ 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 6 time periods of 25 years each. The scarce resources are two grades (high and low cost) 6 different kinds of resources (petroleum, natural gas, coal, shales, $U^{235}$, $U^{238}$), available in each of the two regions. The model is an equilibrium model and for the most part ignores flow constraints (such as the nuclear fuel cycle, penetration curves, lags, etc.)

The macroeconomic assumptions are basically that growth in GNP per capita will continue, but at a diminishing rate over the next 150 years; that population will also slow to reach a world level of 10 billion in 2050; and that the rate of technological change (equal to the rate of growth of per capita GNP) will be the same in all sectors. Finally the discount rate on utility is taken to be zero, but the discount rate of goods is taken to be 10 per cent per annum.

The model just described has been in operation for about two years and has been used for a number of diverse problems. In this paper we will describe how the technique can be used to describe the future buildup of atmospheric contaminants over the medium and long run, as well as to estimate the costs, benefits, and timing of controls.

To implement this change, we need to introduce the three factors discussed in the last section: emissions, diffusion, and standards. To do this we add a second block of constraints into the linear program shown in equations (1) and (2) above. First, let $\gamma(\ell\ell,i)$ be the emissions per unit activity into stratum $\ell\ell$ (in $10^9$ tons carbon per $10^{15}$btu). Then total emissions into stratum $\ell\ell$ in a given period, $E(\ell\ell,t)$ are

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

Next denote $M(\ell\ell,t)$ as the total mass of $CO_2$ (in $10^9$ tons C) in a given stratum, and $D(i,j)$ as the transition probabilities of moving from stratum i to stratum j. From the basic diffusion equations we have

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

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

$$(5) \quad M(\ell\ell,t) \leq St(\ell\ell) \quad .$$

To implement the controls, we used to add equation set (3), (4), and (5) to our original problem in (1) and (2). A complete map of the problem is given in Figure 2 below. Note that for computational simplicity we have constrained the concentration of tropospheric carbon dioxide. This introduces computational inaccuracy in the order of 0.5 percent.

Figure 2. Map of Optimization Problem

Activities:

| Constraints: | $x(i,j,jj,k,\ell,n)$ | $xp(k,\ell,m,n)$ | $xc(m,mm,n)$ | $e(\ell\ell,n)$ |
|---|---|---|---|---|
| $r(i,j,jj)$ | Extraction | 0 | 0 | Emissions from extraction |
| $p(k,\ell,n)$ | Extraction | Conversion | 0 | Emissions from conversion |
| $c(m,\ell,n)$ | 0 | Conversion | Consumption | Emissions from consumption |
| $e(\ell\ell,n)$ | 0 | 0 | 0 | Total emission |
| $m(\ell\ell,n)$ | 0 | 0 | 0 | Mass equations |
| Objective function | Cost | Cost | Utility | |

Variables:
x = extraction
xp = processing
xc = consumption
e = emission

Constraints:
r = resource availability
p = processing balance equations
c = consumption balance equations
e = emissions identity
m = mass diffusion equation

Subscripts:
i= country of resource
j= kind of resource
jj=grade of resource
k= fuel
ℓ= country of consumption
ℓℓ =environmental stratum
m= demand category
mm=step in demand function
n= time period

## V. Results of the Standards Model

In this section we will present the results of the runs with the "standards model" outlined in the last section. Recall that there are four different runs; they differ only in the standards imposed on the concentration of carbon dioxide. In what follows we will be interested in the general timing of the control program, in the problem of feasibility of the control program, and finally on the costs of control, and the effect on energy prices.

### 1. The question of feasibility

The first question to investigate is whether the standards paths are feasible. This question is answered automatically by the linear programming routine, but it is of independent importance.

The question of feasibility rests on the existence of activities which meet the demand constraints 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 the non-fossil fuels have no significant carbon dioxide emissions. In the program discussed above, we consider only nuclear fission as an alternative to fossil fuels, but the results would be identical for any of the other non-fossil fuels (solar, fusion, geothermal) with the same cost structure.

In the program outlined above, it would be possible to set arbitrarily low carbon dioxide standards because the energy system can adapt to these by simply shifting the mix from fossil to nuclear fuels. It should be noted, however, that the model used here overemphasizes the degree of maleability of the system in that it ignores historically built capital equipment as well as the lags and frictions in economic behavior. To be realistic, it is probable that it would take in the order of 25 years to phase out of carbon-based fuels even if a crash effort were instituted, so this places a lower limit on the feasibility of carbon dioxide limitation. Aside from this lag, and assuming the technological relations are correctly specified, however, there are no significant problems of limiting carbon dioxide emissions from a technical point of view.

## 2. Comparison of uncontrolled and controlled programs: quantities

The next question concerns the comparison of the uncontrolled path and the controlled paths. In the program discussed above, we have divided the system into six periods, each with 25 years. The most important question is the timing of the limitations on carbon dioxide emissions. Table 5 shows the paths of emissions and concentrations for carbon dioxide in the atmosphere for each of the four paths.

The first point to note is that the uncontrolled path does lead to significant changes in the level of atmospheric carbon dioxide. According to the projection of the model, atmospheric concentrations in the uncontrolled path rise by a factor of seven (4213/600) over the entire period. This is far above what we assume to be the reasonable limit of a doubling of the carbon dioxide concentration. Put differently, it appears that *if serious problems are likely to occur when the level of carbon dioxide has doubled or more, then the uncontrolled path appears*

Table 5. Carbon Dioxide Emission and Concentration Predicted from Model

| Carbon Dioxide Emission rate ($10^9$ tons, carbon/yr) | 1970 | 1995 | 2020 | 2045 | 2070 | 2095 |
|---|---|---|---|---|---|---|
| 1. Uncontrolled | 2.8 | 9.5 | 36.6 | 75.5 | 180.0 | 74.7 |
| 2. 200% increase | 2.8 | 9.5 | 36.1 | 44.5 | 17.9 | 4.9 |
| 3. 100% increase | 2.8 | 9.5 | 29.9 | 10.7 | 6.3 | 3.9 |
| 4. 50% increase | 2.8 | 9.5 | 10.0 | 4.5 | 2.7 | 1.7 |

| Carbon Dioxide concentration in atmosphere ($10^9$ tons carbon) | 1983 | 2008 | 2033 | 2058 | 2083 | 2108 |
|---|---|---|---|---|---|---|
| Levels | | | | | | |
| 1. Uncontrolled | 43.7 | 177.4 | 698.5 | 1682.6 | 4067.0 | 4212.9 |
| 2. 200% increase | 43.7 | 177.4 | 691.1 | 1192.1 | 1196.5 | 1106.0 |
| 3. 100% increase | 43.7 | 177.4 | 594.7 | 598.1 | 598.4 | 598.6 |
| 4. 50% increase | 43.7 | 177.4 | 298.1 | 299.1 | 299.2 | 299.3 |

to be heading for the danger zone. It appears that the doubling will come around 2030.

It is interesting to compare the calculated path with current estimates of emissions and concentration. Table 6 shows these figures. As is shown, the concentrations are essentially in line with the observed figures, but the emissions are about 25 percent too low. The fact that emissions are too low relates simply to the composition of fossil fuels: in the calculated program there is very heavy use of natural gas and oil and very little coal, while in fact coal accounted for about 25 percent of actual consumption in 1970. The different carbon dioxide composition of the fuels explains the difference in emissions.

The second important point, and perhaps the most surprising one, is that the optimal path does not differ from the uncontrolled path for the first two periods (that is to say the periods centered on 1970 and 1995) and that only in the third period (centered on 2020) do abatement measures become necessary. Put differently, according to the cost schedules assumed in the model, it does not pay to curtail carbon dioxide emissions until the time, or almost the time, when the limit is reached; and for the three cases examined this time comes in the period centered on 2020. This point is important, for it implies that there is still a comfortable amount of time to continue research and to consider plans for implementation of carbon dioxide control if it is deemed necessary.

It is important to understand where the abatement measures would take place in an efficient program. Recall that in the model, there are five fuels (oil, natural gas, coal, electricity, and hydrogen) and these are used in four sectors (electricity, industry,

Table 6. Comparison of uncontrolled model predictions with observed values, 1970 and other projections, 2000

| | 1970 | | 2000 | | |
|---|---|---|---|---|---|
| | Actual | Calculated from model | Calculated from model | Estimated by: Machta (I) | Machta (II) |
| Atmospheric concentration | | | | | |
| In $10^9$ tons carbon | 666. | 667. | 778. | 786. | 827 |
| In part per million | 322. | 322.5 | 376 | 380 | 400 |
| Emission | | | | | |
| In $10^9$ tons carbon | 3.8 | 2.8 | 12.4 | 10.2 | 10.2[b] |

b = implicitly assumed

Sources: Calculated values assume from Machta [1972], p.129 that value for 1958 was 312 ppm (645 x $10^9$ tons c) and interpolated geometrically over the 25 year period centered on 1970. Actual from Machta [1972], pp.128 and 129, excluding cement production from Keeling [1973]. For the year 2000, figures from Machta [1972] for Machta (I) and NCAR [1974] for Machta (II).

Table 7. Fraction of inputs which are carbon-based (fossil fuels), by sector and period, United States

| 25 year period centered on: | Sector: | | | |
|---|---|---|---|---|
| | Electricity | Industry | Residential | Transport |
| 1970: 1 | 100% | 100% | 100% | 100% |
| 2 | 100% | 100% | 100% | 100% |
| 3 | 100% | 100% | 100% | 100% |
| 4 | 100% | 100% | 100% | 100% |
| 1995: 1 | 73% | 100% | 100% | 100% |
| 2 | 78% | 100% | 100% | 100% |
| 3 | 78% | 100% | 100% | 100% |
| 4 | 73% | 100% | 100% | 100% |
| 2020: 1 | 13% | 100% | 87% | 100% |
| 2 | 6% | 100% | 87% | 100% |
| 3 | 0 | 100% | 75% | 100% |
| 4 | 0 | 100% | 0 | 100% |
| 2045: 1 | 0 | 100% | 66% | 100% |
| 2 | 4 | 100% | 0 | 88% |
| 3 | 0 | 93% | 0 | 0 |
| 4 | 0 | 44% | 0 | 0 |
| 2070: 1 | 0 | 100 | 0 | 100% |
| 2 | 0 | 40 | 0 | 0 |
| 3 | 0 | 15 | 0 | 0 |
| 4 | 0 | 6 | 0 | 0 |
| 2095: 1 | 0 | 7% | 0 | 0 |
| 2 | 0 | 11% | 0 | 0 |
| 3 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0 | 0 |

residential, and transport). How will the mix of fuels to the different industries change? Also note that since demand is responsive to price in the model, it is possible that the level of final demand change in those sectors which are supplied by carbon-intensive fuels.

Table 7 indicates in a rough way the changes in the input mix by sector over time. We have shown the fraction of the inputs which are carbon based (i.e. fossil-fuels): This aggregates over the different fossil fuels but gives the best overall measure of the impact of control programs by industry. Interesting enough, the chief difference lies in the industrial sector. Here, coal based fuels are used essentially throughout the period under consideration in an uncontrolled program; as can be seen, however, starting in the fourth period, and especially in the fifth, heavy curtailment of fossil-fuels is necessary, especially in the most stringent control programs. The same general pattern appears in the residential sector in the third and fourth period, and in transport in the fourth period. On the other hand, relatively little change is introduced in the electricity sector, as the transition to non-fossil fuels is essentially completed before the carbon dioxide constraints become binding.

The program calculates, but we have not shown, the effect of the constraints on demand. Recall that demand is somewhat sensitive to price, so that it is possible that demand will be curtailed in order to meet the carbon constraints. A naive view would perhaps hold that since carbon emissions must be reduced by 85 percent from the uncontrolled path, demand must also be reduced by 85 percent.

In fact, this naive view would be almost completely wrong: almost no changes in the demand pattern occur, and almost all the reaction comes about as a result of supply side adjustments. Put differently, the reaction to restrictions on emissions is to change the conposition to production away from carbon-based fuels and not to reduce consumption. The reason for this will become apparent later when we examine the effects on prices.

## 3. Prices and Costs

In an optimization framework, as in an economy, constraints have their costs in terms of the objectives of the optimization. Recall that the control program takes the form of imposing upper bounds on the level of atmospheric concentrations; these are formally imposed as six inequality constraints on the problem (one inequality for each time period). Associated with each of these constraints (as well as all the other constraints) is a dual variable--sometimes called a shadow price--which in the optimal solution calculates the amount, on the margin, that the constraint costs in terms of the objective function. Put differently, the shadow price indicates how much the objective function would increase if the constraint were relaxed one unit.

The most important shadow prices in the carbon dioxide optimization are the shadow prices on the carbon dioxide emissions constraint. The constraints are in terms of $10^9$ metric tons of carbon in the troposphere, while the objective function is real income of consumers in $10^9$ dollars of 1970 prices. This implies that the shadow price has the dimensions of dollars per ton of carbon dioxide emitted into the troposphere.

Table 8 gives the shadow prices for carbon emissions for the four programs during the six periods. First note that the uncontrolled program has shadow prices equal to zero, indicating that the constraint is not binding. Second, note that the prices per ton start very low (between \$0.01 and \$0.15 per ton carbon) and rise to a very high level of between \$130 a ton (1970 prices), by the end of the next century. These should be compared with the prices of carbon-based fuels, which are around \$25 a ton (carbon weight) of coal, \$100 a ton (carbon weight) for petroleum, and \$200 a ton (carbon weight) for natural gas. Roughly speaking, the shadow price only becomes significant in the third period for the two most stringent paths (paths 3 and 4) and in the fourth period for the permissive path 2. Comparing Tables 5 and 8, we note, then, that the shadow prices are relatively low for periods when the concentration constraint is not binding and high in those cases where it is binding.

We may also ask what the effect of the carbon dioxide control program is on energy prices in general. These effects fall into two general categories: effects on factor prices-- in particular royalties on scarce energy resources; and effects on product prices. Table 9 shows the results. Note that the major impact is on factor prices rather than product prices. For example, comparing the shadow prices of the most stringent with the uncontrolled case, note that petroleum and gas shadow prices fall by about ten percent while coal and oil shale royalties <u>fall to zero</u>. By contrast, uranium royalties <u>rise</u> by an insignificant amount (about 0.1 percent) from the uncontrolled to the most stringent program.

Table 8. Shadow Prices on Carbon Dioxide Emission (1970 dollars per metric ton carbon)

| Program | I. Uncontrolled | II. 200% increase | III. 100% increase | IV. 50% increase |
|---|---|---|---|---|
| 1970 | 0.00 | 0.01 | 0.05 | 0.15 |
| 1995 | 0.00 | 0.07 | 0.57 | 1.80 |
| 2020 | 0.00 | 0.87 | 8.24 | 28.20 |
| 2045 | 0.00 | 21.11 | 46.08 | 47.66 |
| 2070 | 0.00 | 58.43 | 42.17 | 42.17 |
| 2095 | 0.00 | 0.00[a] | 132.88 | 132.88 |

[a] Computational problems may mean that this coefficient is incorrect.

Table 9. Effects of carbon dioxide controls on factor and product prices (all prices in 1970 dollars)

Factor prices* (Dollars per $10^9$btu)

| | Program: | | | |
|---|---|---|---|---|
| | I Uncontrolled | II 200% increase | III 100% increase | IV 50% increase |
| Petroleum - US | 21. | 21. | 20. | 19. |
| - Row | 41.4 | 41.3 | 40.9 | 39.9 |
| Natural gas - US | 68. | 68. | 67. | 67. |
| - Row | 6. | 6. | 5. | 5. |
| Coal - US | 1.7 | 1.7 | .2 | 0 |
| - Row | .3 | .3 | 0.02 | 0 |
| Shale - US | 2.6 | 2.6 | 2.2 | 0 |
| - Row | 5.4 | 5.4 | 5.0 | 0 |
| Uranium 235 | 13. | 13. | 13. | 13. |

Product Prices (Dollars per $10^6$ btu)

| | | I | II | III | IV |
|---|---|---|---|---|---|
| Electricity - | 1970 | 3.43 | 3.43 | 3.43 | 3.43 |
| | 2070 | 4.69 | 4.41 | 4.41 | 4.41 |
| Industrial - | 1970 | 0.71 | 0.71 | 0.71 | 0.71 |
| | 2070 | 1.52 | 3.31 | 3.31 | 3.31 |
| Residential - | 1970 | 1.97 | 1.97 | 1.97 | 1.97 |
| | 2070 | 4.00 | 3.72 | 3.72 | 3.72 |
| Transport - | 1970 | 9.02 | 9.02 | 9.02 | 9.02 |
| | 2070 | 15.02 | 16.67 | 16.67 | 16.67 |
| Simple Average - | 1970 | 3.78 | 3.78 | 3.78 | 3.78 |
| | 2070 | 6.31 | 7.03 | 7.03 | 7.03 |

*Each category refers to the most economic grade of resource, except for petroleum and natural gas where they refer to the value of undrilled resource.

Final product prices generally show a more modest rise, with industrial prices showing most dramatic change (a 119 percent rise). Overall, product prices rise by about 11 percent from the uncontrolled to the controlled case for the fifth period.

A final question regarding shadow prices may appear rather strange: What are the shadow prices by stratum? This refers to the shadow prices in the different regions of the earth (atmosphere, mixed ocean, deep ocean, etc.). Table 10 shows the shadow prices for three periods and for each of the seven strata, again in terms of prices per ton of carbon. These indicate the cost that would be incurred by an increase of one ton of the mass in a given stratum. Thus the price for carbon in the troposphere in 2045 would be \$45, while in the long-term biosphere it would be \$15.

The important point about Table 11 is that there are for all intents and proposes only three economically interesting strata: the deep ocean, the long-term biosphere, and the rest of the strata. And the most interesting conclusion is that the cost of putting carbon into the deep ocean is only about one-hundredth of the cost of putting it into the atmosphere. The reason for this anomaly is simply that by the time carbon is put into the deep ocean it is locked up there for about 1500 years on average. The price in the long-term biosphere is also significantly below, approximately one-third, of the price in the other strata.

The implications of this finding about the shadow prices in different strata are quite interesting. It says that on the margin, and taking 2045 as an example, if we could take emissions from the atmosphere and move them into the deep oceans it would

## TABLE 10. DUAL VARIABLES ON EMISSIONS (DOLLARS PER TON, 1970 PRICES)

| | PERIOD CENTERED ON | | |
|---|---|---|---|
| | 1970 | 2045 | 2095 |
| TROPOSPHERE | 0.2 | 44 | 133 |
| STRATOSPHERE | 0.2 | 45 | 124 |
| MIXED LAYER OCEAN | 0.1 | 45 | 125 |
| DEEP LAYER OCEAN | 0.008 | 0.43 | ~1 |
| SHORT-TERM LAND BIOSPHERE | 0.2 | 45 | 124 |
| LONG-TERM LAND BIOSPHERE | 0.1 | 15 | 37 |
| MARINE BIOSPHERE | 0.2 | 42 | 118 |

pay if this could be done for less than $44 per ton. Similarly, if we could simply remove the carbon and put it into trees, which would rot and gradually add the carbon back into the atmosphere, this would be worth a subsidy of no more than $30 per ton.[1] These results can be used to evaluate processes, such as those proposed by Marchetti discussed above, to shortcircuit the distribution of carbon dioxide by placing it in the deep ocean. Given some preliminary estimates of the costs of these processes, it appears that they merit considerable attention. These results also suggest that such events as the Green Revolution, which dramatically increases yields in the short-term biosphere, would have essentially no effect in reducing the carbon dioxide problem: this result is simply due to the fact that the decay time of annual crops is so short that the total reduction of the atmospheric concentration of carbon dioxide is negligible.

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 also examine the value of the objective function to determine the overall cost. Table 9 gives the calculation of the overall cost calculated both by the marginal method and by use of the objective function. Clearly the control of carbon dioxide is not free--the medium control program II has discounted costs of $37 billion in 1970 prices. On the other hand, the cost as a fraction of world GNP is likely to be insignificant, less than 0.2 percent in the most stringent case. If the energy sector comprises 5 percent of the economy, this implies the cost of meeting energy demands has been raised by no more than 3 percent.

---

[1] In terms of discounted costs, the shadow price of carbon falls about 3.3 percent annually (e.g. the discount rate minus the rate of increase of the carbon price in constant prices is about 3.3 percent). Thus if we contain carbon for 40 years (the average lag for the long-term biosphere) cost in 2045 is around 45 (exp(-.033x40)) = 15.

Table 9. Cost of Carbon Dioxide Control Programs

(billions of dollars, 1970 prices)

| | Path: I (Uncontrolled) | II 200% increase | III 100% increase | IV 50% increase |
|---|---|---|---|---|
| Discounted total cost: | | | | |
| a. From objective function | 0 | 15 | 37 | 93 |
| b. From dual variables ("marginal method") | 0 | 19.5 | 78.5 | 120.0 |
| (a) as fraction of discounted world GNP: | 0 | .0003 | .0005 | .0014 |

Note: The table gives two different ways of calculating the total cost of the carbon dioxide control program. The first method (the objective function method) simply calculates the value of the objective function in the different programs. The marginal method calculates the value by multiplying the carbon dioxide constraints by the shadow prices and summing over all carbon constraints. The difference between the two indicates that the average cost is below the marginal cost.

## 4. Summary

To summarize, we have indicated what the efficient program for meeting certain carbon dioxide standards is in a long-term energy model. These indicate that for reasonable standards (limited to between a 50 percent and a 200 percent increase in the atmospheric concentration) the program appears feasible. Moreover, it is a program which requires no changes in the energy allocation for the first two 25 year periods, and only in the third period, centering on 2020,do modifications in the allocation take place. These modifications take the form of reducing the fossil fuel use in the non-electric sector, and replacing it with non-fossil fuels.

Moreover, it appears that the efficient programs have rather high implicit shadow prices on carbon dioxide emissions but that the total effect on energy prices and the total cost of meeting the energy bundle of goods is relatively small. It appears that a rise in the final price level for energy goods of in the order of 10 percent is the range of estimates for the three programs investigated here.

Subject to the limitations of the model used here, then, we can be relatively optimistic about the technical feasibility of control of atmospheric carbon dioxide. If the control program is instituted in an orderly and timely way, the world energy system can adopt to controls of the magnitude examined here without serious dislocations. It remains to be determined what a set of optimal controls would be, and how these controls could be implemented.

## References:

[1] Budyko [1974a]. M.Budyko, "Our Changing Climate", 1974

[2] Budyko [1974b], M.I.Budyko, *Climate and Life*, Academic Press, New York and London, 1974, chapters 3-5,9.

[3] Keeling [1973]. Charles D.Keeling, "Industrial Production of Carbon Dioxide from Fossil Fuels and Limestone", Tellers (XXV,2), 1973, pp.1974-198

[4] Lamb [1972]. H.H.Lamb, *Climate: Present, Past, Future*, Vol.I, Mellmen & Co.Ltd., London, 1972

[5] Machta [1972]. Lester Machta, "The Role of the Oceans and Biosphere in the Carbon Dioxide Cycle", Nobel Symposium 20, pp.121-145

[6] Manabe and Wetherald [1967]. S.Manabe and T.T.Wetherald, "Thermal equilibrium of the atmosphere with a given distribution of relative humidity", Journal of Atmospheric Sciences, vol.24, 1967, pp.241-259

[7] Matthews et al. [1971]. W.H.Matthews, W.W.Kellogg, and G.D.Robinson, *Man's Impact on the Climate*, MIT Press, Cambridge, USA, 1971

[8] NCAR [1974]. National Center for Atmospheric Research, Atmospheric Implications of Energy Alternatives, UCAR Forum, October 1974

[9] NCAR [1975]. National Center for Atmospheric Research, *Atmospheric Implications of Energy Alternatives*, Boulder, USA, February, 1975.

[10] Nordhaus [1973]. William D.Nordhaus, "The Allocation of Energy Resources", *Brookings Papers on Economic Activity*, 1973: 3, pp.529-570

[11] PSAC [1965]. President's Science Advisory Committee, *Restoring the Quality of our Environment*, *Report of the Environmental Pollution Panel*, Washington: Government Printing Office, 1965.

[12] Sellers [1974]. William D.Sellers, "A Reassessment of the Effect of $CO_2$ Variations on a Simple Global Climatic Model", *Journal of Applied Meteorology*, October 1974, pp.831-833

[13] Singer [1970]. S.Fred Singer, *Global Effects of Environmental Pollution*, D.Reidel, Dordrecht-Holland, 1970