CLIMATIC CHANGE AND THE CARBON WEALTH OF NATIONS

Jesse Huntley Ausubel

April 1980
WP-80-75

INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
A-2361 Laxenburg, Austria

PREFACE

Climatic change has been a topic of interest to IIASA for some years. The issue first arose in relation to possible interactions between the global climate and the various energy futures described as part of the IIASA Energy Systems Program (ENP). Greatest interest focused on the effects on climate of increasing amounts of carbon dioxide in the atmosphere. The significance for the climate and for energy strategies of the potential future release of large amounts of CO_2 from burning of fossil fuels was explored at a conference on the theme of "Carbon Dioxide, Climate, and Society" in February of 1978. More recently the Resources and Environment Area has joined the ENP in research in this area and focused on the theme of climatic constraints and human activities. On the one hand, how should society respond to possible anthropogenic climatic change, prevention, compensation, or adaptation? On the other hand, how can we estimate the consequences of climatic change and variability for agriculture and other important human activities? A Task Force meeting on this theme was held in February of 1980. The research for this paper was undertaken at IIASA as part of the Global Climate Task of the Resources and Environment Area during the Summer of 1979 and early part of 1980.

SUMMARY

A great deal of research is currently going into simulating the effects of increased atmospheric carbon dioxide on climate. This research considers the direct climatic effects of steadily rising atmospheric concentrations of carbon dioxide and usually assumes a rate of carbon dioxide increase from burning of fossil fuels which will lead to a doubling of airborne concentrations by some time in the first half of the twenty-first century. Such a rate is consistent with observations of carbon dioxide increases in the recent past, but it also depends crucially on implicit assumptions about the future functioning of the world economy. But, rather than make assumptions about the world economy, one can try to work backward from the carbon dioxide demanded for a mid-twenty-first century climatic change toward the physical carbon resources. Where in the earth will the carbon come from? How is it distributed with respect to present national and regional boundaries? Can this tell us something about the likelihood of realization of a CO_2 problem? About the possibilities for its control? And, when combined with estimates of past contribution by geopolitical entities, does it tell us anything about responsibility for a CO_2-induced climatic change?

CONTENTS

INTRODUCTION

There are three basic ways in which human activities may affect the climate. One is by releasing heat into the atmosphere. A second is by changing the physical and biological properties of the underlying surface. Finally, changing the composition of the atmosphere may alter the climate. It is believed that at present, releases of heat are responsible only for local effects, and are likely to remain so for the next couple of generations (Williams et al. 1979). There is the possibility with respect to alterations in albedo and other surface changes, such as the conversion of North America from forest and prairie to city and farm, that they have had effects on large-scale climate. The data, however, is not available to validate the hypothesis. The greatest and still increasing concern is that growing measurable changes in the composition of the atmosphere may lead to significant modification of climate on a global scale by the middle of the next century. Our most uneasy state of blended interest, uncertainty, and apprehension exists with respect to carbon dioxide.

A great deal of research is currently going into simulating the effects of increased atmospheric carbon dioxide on climate. This research considers the direct climatic effects of steadily rising atmospheric concentrations of carbon dioxide and usually assumes a rate of carbon dioxide increase which will lead to a doubling of airborne concentrations by some time in the first half of the twenty-first century. Such a rate is consistent with observations of carbon dioxide increases in the recent past, but it also depends crucially on implicit assumptions about the future functioning of the world economy. But, rather than make assumptions about the world economy, which is the approach taken by, for example, Rotty (1979) and the Panel on Energy and Climate of the U.S. National Academy of Sciences (1977), one can try to work backward from the carbon dioxide demanded for a mid-twenty-first century climatic change toward the physical carbon resources. Where in the earth will the carbon come from? How is it distributed with respect to present national and regional boundaries? Can this tell us something about the likelihood of realization of a CO_2 problem? About the possibilities for its control? And, when combined with estimates of past contribution by geopolitical entities, does it tell us anything about responsibility for a CO_2-induced climatic change?

In this paper, we shall examine the "carbon economy" and make some tentative estimates of the "carbon wealth" and potential carbon dioxide contributions of nations and regions. First, we shall look briefly at the nature of the carbon economy and the CO_2 question from a geophysical point of view. Then, we shall try to estimate its extent and potential in the biosphere and in respect to fossil fuels. Finally, we will look at some arguments about why or why not this economy will be regulated, with particular attention to the distributive issues of carbon wealth and climatic change.

The Natural Economy of Carbon

The perspective from which the potential problems of the changing composition of the atmosphere is now often approached is that of "biogeochemical" cycles, or more accurately, circulations. Such a perspective takes a kind of corporate view of the earth, in which one looks at the various chemical reservoirs of the earth as organs (Cowling, Crutzen, Garrels, and Likens 1979). Among these organs, namely the atmosphere, oceans, biosphere, and lithosphere, there is a life-giving circulation of elements. Indeed, this circulation is a kind of metabolism of the earth's surface environment. On varying time scales, this circulation includes the air; the oceans, estuaries, surface, and groundwaters; the bottom sediments of the earth, its soils, and the rocks of the crust; and all of the living organisms that inhabit the water and soils and cover the land over the surface of the earth. All the various chemical elements take part in the circulation, but of particular concern are those elements which are essential or detrimental to plant and animal life. Thus, the most widely studied circulations include carbon, nitrogen, phosphorus, sulphur, and some metals such as mercury, lead, and aluminum.

Because the biogeochemical circulation consists of the movements of these elements within and among the several environmental media (air, water, soil, and biota), the circulation includes various kinds of movements appropriate to the different media. Circulation takes place in certain forms through the various levels of the atmosphere and oceans; it takes quite different forms over and through the land surface. The substances moving within and among these various reservoirs may exist in the form of gases, liquids, or solids. The elements themselves may be in vapor or liquid phase or may exist as particulate matter suspended in gases or liquids.

The biogeochemical exchanges among the different environmental media take place through many different physical and biological processes:

> The physical processes include evaporation, volatilization, combustion, precipitation, absorption, dissolution of gases and solid substances in liquids, gravitational settling of particles and aerosols, laminar and turbulent flow of matter in air and ocean currents, as well as flows of rivers and streams. The biological processes include photosynthetic and metabolic fixation and release of essential elements, transpiration and respiratory mechanisms, cellular absorption and secretory processes, biological weathering, ballistic and nonballistic dispersal of pollen, spores, hyphal fragments, and microbial cells in air, powered mobility of vertebrates and invertebrates that can range from amoebic movement through activity of burrowing organisms to migratory movement of large vertebrates. (Cowling et al. 1979)

Of the various environmental media, the atmosphere may be the leading transport medium for key biogeochemical materials on time scales of importance to mankind. The atmosphere is a key channel between the source and storage reservoirs of soil, water, and biota. Moreover, the composition of the atmospheric reservoir is crucially determined by biologic processes occurring all over the earth. For instance, carbon dioxide is released to the atmosphere during respiration and removed from the atmosphere through photosynthesis and fixation of carbon. Oxygen, nitrogen, sulfur, and phosphorus are also circulated between the biosphere and atmosphere, and the many atmospheric trace gases along with their photochemical and intermediate metabolic products in which these elements play a role, are important factors in the functioning of the atmosphere.

One may say that there is a "natural," or extra-human, circulation of biogeochemical elements. The volume and direction of the movement depends on the chemical and physical properties of the substances, and on the action of winds, waves, animals, and so forth. The "natural" circulatory rates of the biogeochemical elements vary widely. For example,

> ...atmospheric carbon dioxide is renewed in a few years; the ocean renews itself in approximately 1000 years; oxygen is renewed in a few million years; and sodium in the ocean is regenerated approximately every 200 million years. (Cowling et al. 1979)

It has been suggested that in the prehuman environment, concentrations of these components in the global systems presumably fluctuated around some mean condition in the absence of large perturbations.

Human activity has greatly altered global patterns of biogeochemical circulation. These alterations have occurred in many ways, including combustion of fossil fuels, clearing and tilling of land, burning of vegetation, mining and melting of minerals, changing the natural water courses of the earth, irrigating land, and application of chemicals to the biota in the form of fertilizers, pesticides, and growth regulators. Moreover, human activities have greatly accelerated global rates of biogeochemical circulation. Thus, because of the limited "metabolic capacity" of the various reservoirs on various time scales, the impact of human activities has been to transfer biogeochemical materials from one reservoir to another. For example, in the atmosphere the concentrations of many trace gases and aerosol particles have been altered.

One summary of the carbon reservoirs and circulation is offered by figure 1 and table 1 (Bolin et al. 1979). It is estimated that at the present level of concentration, there are about 700 billion tons of carbon in the atmosphere. A roughly equal amount is estimated to be stored in living biomass on land and a substantially larger amount in soil and humus. A similar amount is held in the surface waters of the ocean, and much larger amounts are held in the deep waters and in the solid earth, where it is mostly in the form of fossil fuels and shale.

It is helpful to see the issue of the changing composition of the atmosphere from this broad physical perspective. At the most general level, one might describe the issue of CO_2 and climatic change as a problem of accelerated carbon circulation, or transfer of carbon from one reservoir to another. As has been suggested, there is a natural flux and circulation of carbon between reservoirs, but on human time scales, most of the carbon may be considered held out of circulation.

Why are human beings suddenly a potentially critical factor in the carbon cycle? Why are we transferring additional carbon from the lithosphere and the biosphere to the atmosphere? At the most elementary level it is a question of conservation of mass. While economic activity may often be said to "consume" fuels or forests, this term is in a profound sense misleading. As Kneese and Schultze have written (1975):

> ...matter is created or destroyed only in the most minute amounts. Man uses the materials of nature in various ways--he eats and drinks them, heats them, and combines them into manufactured goods--but he does not physically destroy them. He consumes the

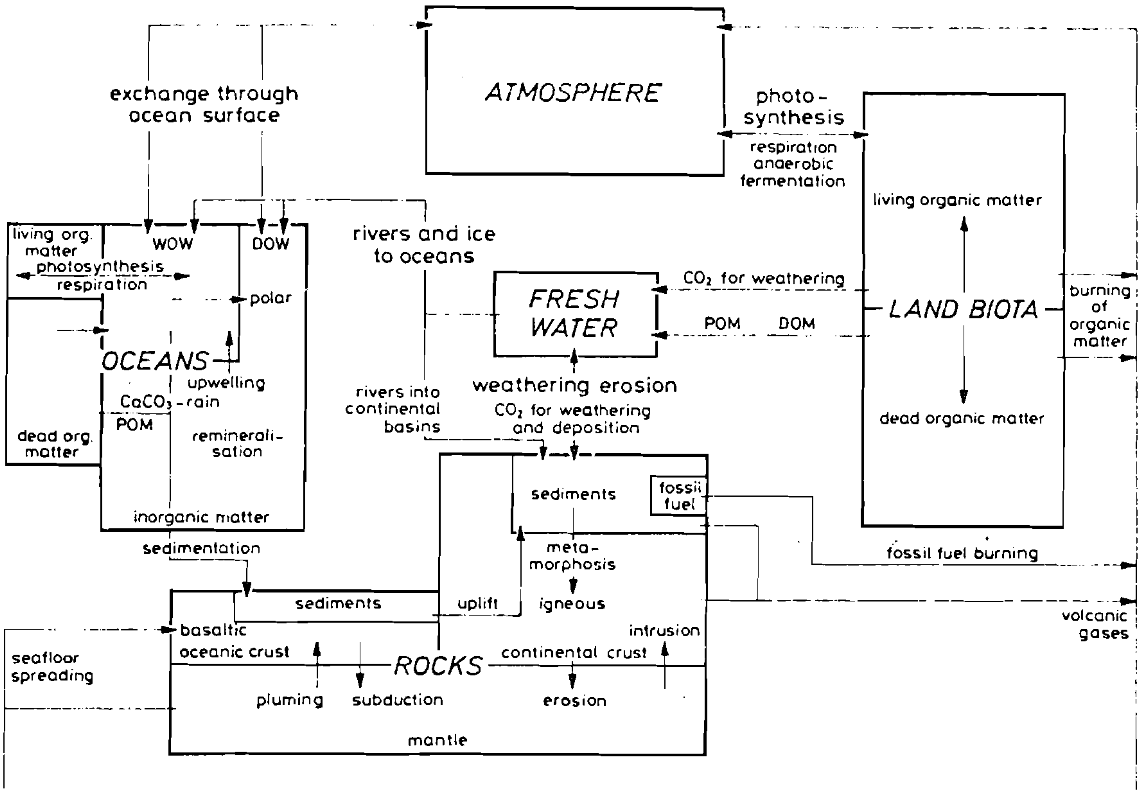


Figure 1. Principal reservoirs and fluxes in the carbon cycle (WOW = warm ocean water; COW = cold ocean water; POM = particulate organic matter; DOM = dissolved organic matter).*

Table 1. Major carbon reservoirs and fluxes.*

Reservoirs		10^{15}g C
Atmosphere: Before 1850		
Common assumption:	290 ppm	610
Stuiver (1978) / Chapter 15, this volume	265 ppm	560
1978	329 ppm	692
Oceans: Total amounts, inorganic		35 000
Above thermoclinic, low and middle latitudes		600
Dissolved organic matter, Chapter 11, this volume		1 000
Particulate organic matter, biomass, Chapter 10, this volume		3
Land biota: Whittaker and Likens (1975)		827
Bazilevich *et al.* (1970)		976
Duvigneaud, this chapter		592
Soil, humus: Keeling (1973a)		1 050
Bohn, 1978		3 000
Duvigneaud, this chapter		2 840
Sediments: Total		>10 000 000
Available for dissolution in oceans		
Broecker and Takahashi (1977)		4 900
Fossil fuels		>5 000
Fluxes		10^{15}g C/year
Atmosphere: oceans, gross exchange		100
Atmosphere: land biota, photosynthesis		
Whittaker and Likens (1975)		53
Bazilevich *et al.* (1970)		78
Duvigneaud, this Chapter		63
Ocean photosynthesis: Chapter 10, this volume		
maximum		126
minimum		15
adopted average		45
Lands to oceans: Chapter 12, this volume		
dissolved inorganic matter		0.4
dissolved organic matter		0.1
particulate organic matter		0.06
Deposition in oceans: Peng *et al.* (1977)		1–10
Fossil fuel combustion, 1978		5

*Source for Figure 1 and Table 1: Bolin et al. *Global Carbon Cycle*, 1979:4-5.

> services or utilities that physical objects yield, but not the objects themselves. Materials come from nature, are used, and are returned (usually in different form) to the earth, the air, or the water, as "residuals"...

While economics has traditionally looked at production and consumption as activities in a way abstract from nature, it is increasingly obvious that economics, at the same time that it must acknowledge the non-physical character of many economic attributes or utilities, must also observe the unity of nature, and man's responsibility in nature, and become in some sense a "physical" science. Economics is not just a matter of balances of utilities, or money, or quantities of wheat but, as Kneese, Ayres, and d'Arge (1970) have pointed out, of balances of materials and energy. Ayres (1978) has suggested that the economy needs to be viewed as

> ...a set of transformations of physical materials from the raw state through successive stages of extracting and processing to goods and services, and finally to return flows consisting of wastes (which may or may not be recyclable). The problem of optimization is correspondingly broadened. This broader theory must address the problem of production of externalities as well as economic services, and the allocation of such externalities in a general equilibrium context. It must deal with the problem of defining and maximizing social welfare subject to resource supply constraints, laws of thermodynamics, and the existence of pervasive externalities resulting from waste residuals; and it must provide theoretical tools to facilitate our understanding of the appropriate mechanisms for managing the economy.

We may see this approach in a way as the economic corollary of biogeochemical circulations.

At present it seems that from both a biogeochemical and economic point of view the most interesting circulation is that of carbon. The carbon of the earth, especially coal, oil, gas, and biomass (wood and so forth), is an enormous store of wealth. Of course, not all the earth's carbon may be regarded as wealth in the realm of mankind. For example, bottom sediments in the oceans, or coal too deep to mine, or certain deposits of peat may not (at least now) be considered wealth, but any carbon which possesses the potential for transformation into a good exchangeable for other goods in an economic system or any deposit of carbon which may enter the carbon circulation on time scales of human civilization may be considered to be a store of value in our analysis. And when carbon undergoes combustion, some of its wealth is released for human uses, primarily in the form of energy. Carbon compounds are also released, to be disposed of in the atmosphere, oceans, and biosphere. In theory, in analyzing the amount of wealth released by the combustion of carbon, one should net out all externalities, especially environmental consequences, such as climatic change resulting from physical redistribution of carbon.

Unfortunately, both our current scientific and economic observation of nature are inadequate with respect to problems like the carbon cycle and climatic change. (Meyer-Abich 1979) The unity of nature is conceived inadequately in the different disciplines necessary for analyzing the physical problem, as well as in dealing with nature economically, and, in any case, the categories of what is good or bad, and what is detrimental or not, do not occur in the sciences. So, man continues to accelerate the carbon circulation, unsure whether to reduce, on account of CO_2, his evaluation of the evident benefits of the carbon economy. For these reasons, and others, a number of writers, as we shall see later, have been extremely pessimistic about the prospects for limiting the transfer of carbon from the reservoirs in the lithosphere and biosphere to the atmosphere. Do the economic geography of carbon and the structure of the carbon economy justify this view? First, let us briefly review the specifics of the CO_2 issue.

Physical Aspects of the CO_2 Question

The CO_2 question has many aspects, several of which may need to be clarified before sound policy decisions about the issue can be made. These include:

- -- the rate of introduction of CO_2 into the atmosphere from fossil fuel combustion and from deforestation and changing land use practices;
- -- modeling of the global carbon cycle, and prediction of levels of CO_2 remaining in the atmosphere for various scenarios of input;
- -- prediction of climatic changes due to increased atmospheric CO_2;
- -- study of the effects of climatic change and increased CO_2 levels on the environment and human activities;
- -- study of possibilities for restriction or abatement of CO_2 emissions through economic and technical controls.

Carbon dioxide is an important natural factor in controlling the temperature of the atmosphere. While it is nearly transparent to visible light (the form of much of the incoming radiation from the sun), carbon dioxide is a strong absorber of infrared radiation, especially at wavelengths between 12 and 18 μm, where a considerable proportion of the outgoing radiation from the earth's surface is transmitted to outer space. (Keeling and Bacastow in NAS 1977) Because of this capacity to trap heat, and, if concentrations increase, possibly raise the temperature of the lower atmosphere, carbon dioxide is often referred to, not entirely accurately, as "a greenhouse gas."

Practically the only established fact of the CO_2 issue is the increase in atmospheric concentrations. The mean monthly concentrations at Mauna Loa (see Figure 2) are the most often

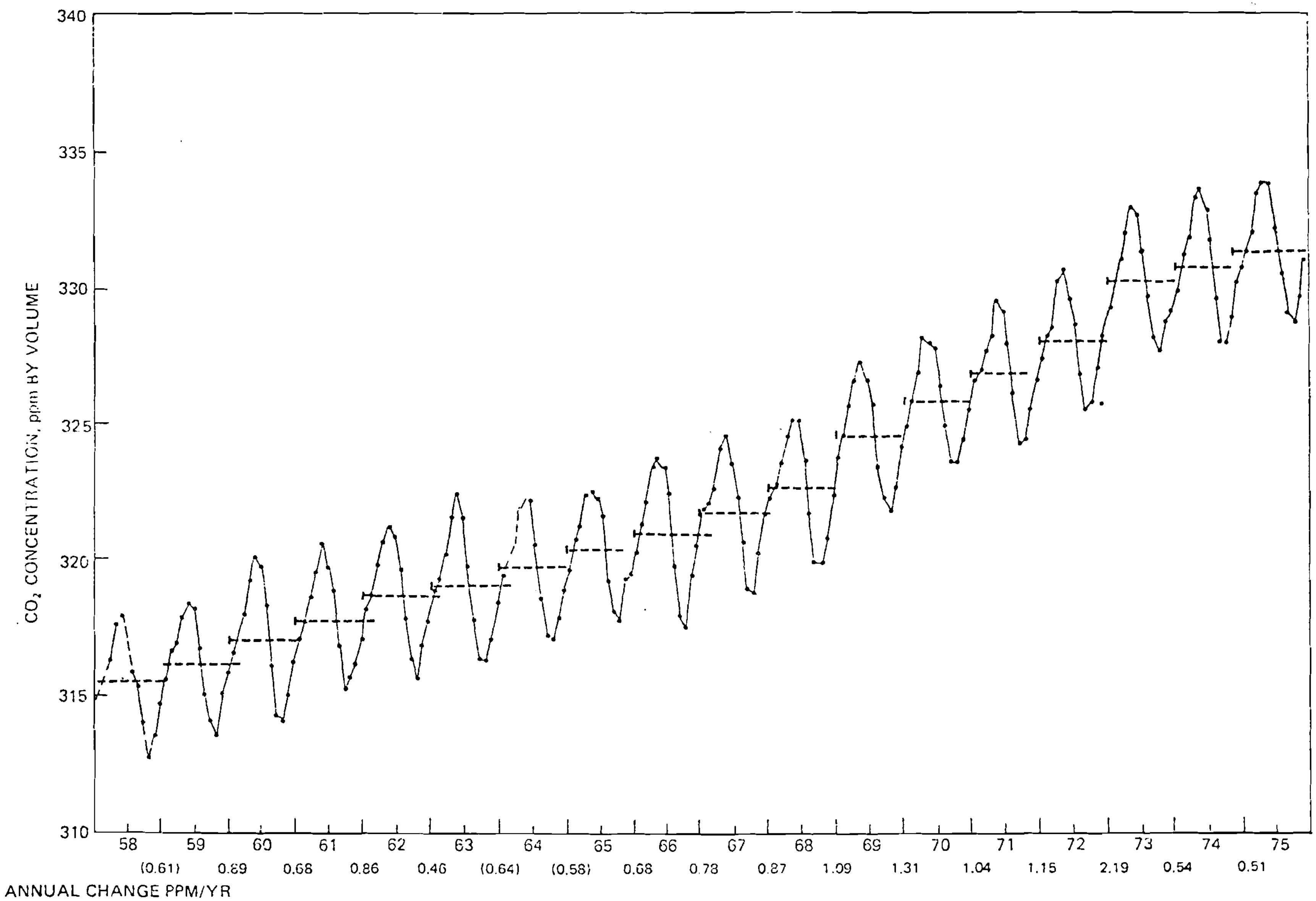


Figure 2. Increase on CO_2 concentration, 1958-1975. (Based on Scripps 1974 Manometric Calibration)

cited, but this general upward trend has also been observed at Point Barrow, Alaska, and the South Pole, as well as in the middle atmosphere by aircraft from the University of Stockholm. The long-term growth rates of all these clean air stations is virtually the same. The seasonal cycle which is so apparent in the figure is explained by the uptake of CO_2 during photosynthesis and its return to the atmosphere when the organic matter rots or otherwise oxidizes.

Based on the measurements of the past 20 years in changes in parts per million, the overall number of tons of CO_2 going into the atmosphere can be estimated. It is at this point that the first crucial association is made. If we take the figures for annual production of CO_2 from fossil fuels and cement* of Keeling and Rotty (Figure 3), the nature of the CO_2 issue immediately emerges. The inference is that a little over half the fossil fuel output has remained in the atmosphere. It is the startling upward trend of these two graphs which has drawn attention to CO_2.

It should be noted that there is a lively debate on the exact dimensions of the so-called airborne fraction. Most scientists had either supposed or concluded that the remaining 45-50% of the CO_2 was consumed by the oceans and the biosphere. Recently, several researchers have argued that the biosphere, far from being a sink for CO_2, has been a major source, as a result of changing land-use and deforestation. (Woodwell et al. 1978) Recent work by Broecker et al. indicates that the biosphere has not been a significant source of CO_2 during the past 20 years. (Broecker et al. 1979) Indeed, according to Broecker's calculations, the biosphere should have absorbed between 5 and 10% of the fossil fuel output. Stuiver's estimates based on the stable carbon isotope record from tree rings suggest that the biosphere was a net source of CO_2 prior to about 1945 and has had little influence since then. (Stuiver, 1978) Revelle and Munk's calculations indicate that up to A.D. 1975 the total quantity of organic material in the biosphere should have remained relatively constant since 1860. (NAS 1977) In contrast, Freyer (1978), whose work is also based on tree ring isotope records, finds the biosphere to be a source, and some of Woodwell's estimates show that the effects of deforestation may have been many times that of the CO_2 released from fossil fuels during the past 50 to 100 years. The airborne fraction of fossil fuel CO_2 input to the air has been used to calibrate the rates of exchange in many carbon cycle models. Most or all of the remaining portion is presumably taken up by the oceans. If deforestation is contributing a significant additional amount of CO_2 to the atmosphere, then the oceans are the only remaining possible sink. This controversy is scientifically a very exciting one and leading to important new insights into the functioning of the biosphere and the oceans, and for the purposes of this paper it is of some significance. The controversy, if resolved, may mean a shift in the projected timing of the doubling of atmospheric CO_2 by a few decades (other

---

*This paper does not treat the role of cement in terms of carbon wealth, as it is very minor.

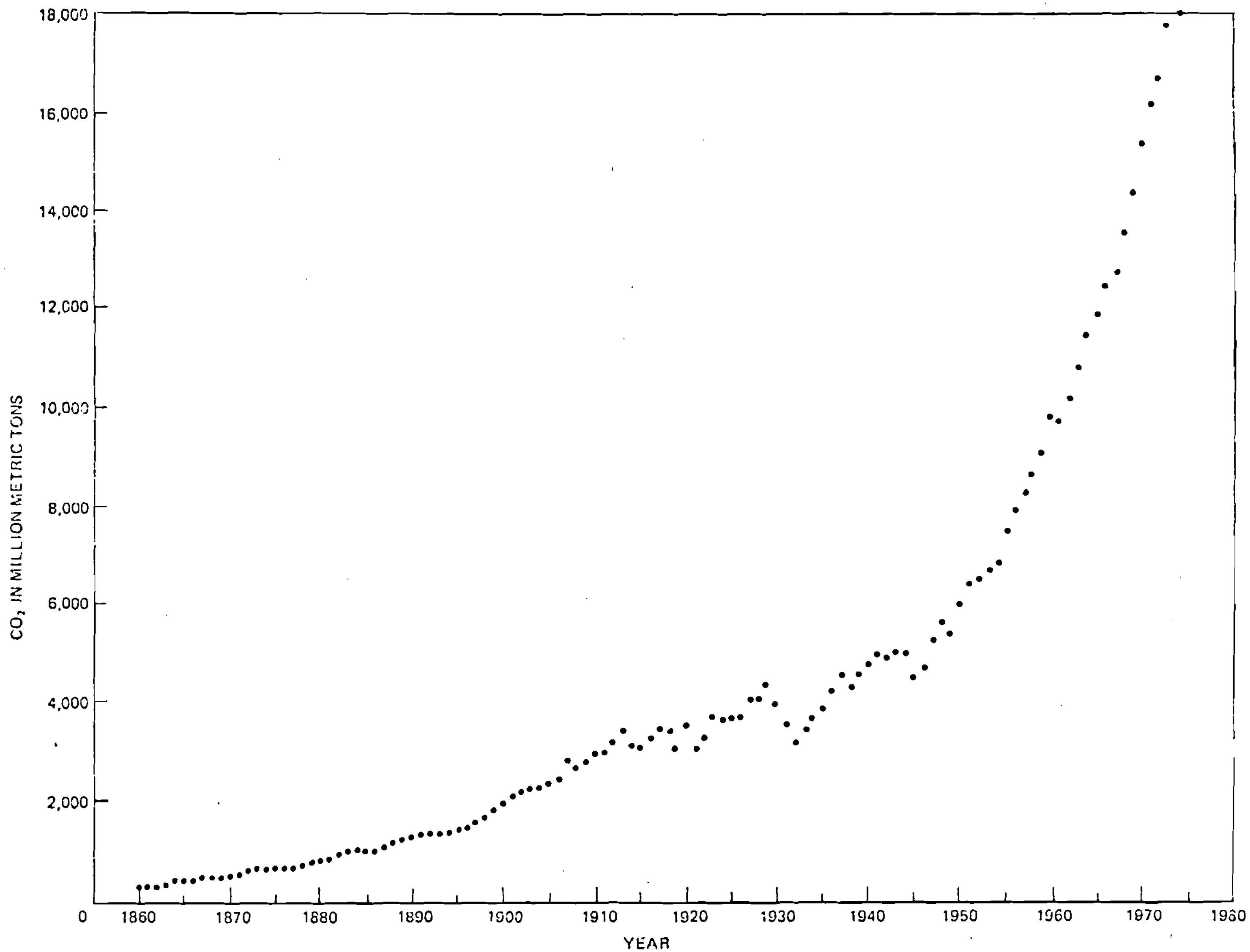


Figure 3. Annual production of CO_2 from fossil fuels and cement. (Source: Keeling 1860-1959; Rotty 1960-1974)

things being equal), which may be important from the point of view of economic adjustment and adaptation and the urgency for preventive or compensatory strategies. The consensus remains that atmospheric CO_2 will reach double its present value some time around the middle of the next century, if the present growth coefficient for the use of fossil fuels is maintained.

While fundamental arguments about carbon cycle models are prominent, there has been a surprising similarity of views about the broad effects of increased CO_2 on global climate. Modeling studies indicate that there will be an increase in mean annual surface temperatures by 2 to 3°C for each doubling of atmospheric CO_2 and that the increases will be considerably greater than this at high northern latitudes. Speculation then begins. Munn and Machta (1979) offer the following possibilities:

- -- Altered precipitation and evaporation regimes. Although the locations cannot be forecast, it is very likely that there will be regional differences and that some areas may show a decrease in precipitation even if (as is expected) the global average increases.
- -- Recession of snow-lines or even disappearance of mid-latitude glaciers.
- -- Except for the possibility that the warming might develop some dynamic instability in the West Antarctic ice cap, most glaciologists do not foresee rapid land-ice melting and consequent sea-level rise. The year-round absence of arctic sea-ice remains a possibility and this may produce secondary climatic effects (such as more snow) especially in neighboring arctic land masses.
- -- Warming of arctic surface waters could disturb the oceanic circulation with consequent reduction in the upwelling process.

The most recent results of Manabe and Wetherald (1979), using a seasonal, coupled ocean-atmosphere model with variable ocean temperatures, variable sea-ice extent, and other interactive features of the atmosphere-hydrosphere-cryosphere system, are very suggestive. For the doubled CO_2 situation global annual mean surface temperature was 2 to 3°C above the present day value. Greater temperature increase occurred at high northern latitudes and during the winter with resulting marked latitudinal assymetry in temperature increase. At the tropopause temperature increases were small, while in the stratosphere large temperature decreases occurred. There was a significant rise in evaporation with the increases fairly uniformly distributed latitudinally. With respect to precipitation there was also an overall increase, but the changes were not uniformly distributed. The greatest increases were in high latitudes. The global mean wind stress was not much different from today. This last result contrasts with the arguments of some scientists who have suggested that with a reduced latitudinal temperature differential, circulation should become more sluggish. Such a change could be important because of the role of wind stress in the ocean currents, which are responsible for a large amount of latitudinal heat transport.

In general, there is considerable uncertainty in the magnitude of these effects and in their spatial patterns. Moreover, there are weaknesses in the models. None of the models adequately accounts for the hydrosphere, especially the thermal buffering capacity of the oceans and the behavior of ocean currents. (NAS 1979) There is considerable uncertainty with respect to feedback effects due to changes in cloud cover. Modeling of the cryosphere needs to be improved. And, while the growth of CO_2 is assumed to be gradual, so far all calculations have been made on the basis of two discrete cases, one with pre-industrial CO_2 concentrations and then usually one with a doubling. These are assumed to be steady states. The potentially different transient intermediate states remain to be explored.

The Assumption That a CO_2 Problem Is Inevitable

While the understanding of the carbon cycle and prediction of climatic changes have many uncertainties, it is nonetheless possible to think about what the consequences of a climatic change might be and evaluate their seriousness. The potential dimensions of the most severe scenario are suggested by the fact that the northern hemisphere sea-ice has been present for millions of years and the conjecture that the cause of the rise in sea level of about 5-7 meters during the Eemian period (about 120,000 years ago) was a melting of the West Antarctic ice sheet. Such a melting could occur in a few centuries or less, and is the one really catastrophic possibility associated with the CO_2 issue. But the more likely and moderate consequences--redistribution of agriculture, water resources, fish stocks, changes in occurrence of pests and pathogens, and so forth--are not to be taken lightly, particularly if the world is already increasingly engaged in tense competition for resources.

Nevertheless, there is a tendency in current discussion to dwell on the inevitability of CO_2-type problems: we must become accustomed to the existence and idea of an increasingly altered environment and therefore put emphasis on the study of adaptation and relevant planning in food, energy, and human settlements. While some meetings on the question of climatic change (Dyson and Marland, Miami 1977, in Dept of Energy 1979) included examination of mechanisms for stopping the physical change from taking place, there seems to have been a shift more recently to acceptance of the change. Thus, a recent AAAS Workshop (Annapolis 1979) has lead to the identification of the following issues for study:

1. How can the nation and world develop strategies for mitigating losses associated with as yet unknown disruptions? How can institutions be made more robust and helped to adjust quickly to the changes presented by a climatic shift?
2. Scenarios will likely be used extensively in analyzing the economic effects of climatic change, as well as the evaluation of many other social issues. How can scenarios be constructed and evaluated? How can they be based on systematic thinking and avoid haphazard or arbitrary judgments?

3. What are the magnitude and type of current strains (strains caused by increased flows of goods and services, of capital, and of labor) on the international system? Is some major international agreement required to accommodate these increases? How will the additional burden of climatic change relate to this stressed system and what mechanisms can be suggested for resolving the associated problems?

What is behind the belief that adaptation is the realistic option, when several reactions are possible by societies to the CO_2 issue? First, let us identify more clearly the possible reactions. At the extremes of reaction are prevention and adaptation. Prevention of climatic change would involve cessation of CO_2 generating activities, and would thus be manifested in such specific policies as restriction of agricultural burning, and support for energy conservation, nuclear energy, and/or solar energy. Adaptation requires nothing to be done to stop the climatic changes in question, but rather that we fit our activities to a changing climate. In between are abatement and compensation, which allow CO_2 generation but would try to diminish climatic change by, for example, developing additional physical sinks for CO_2 to match increasing sources or by unilateral reduction of emissions. After Meyer-Abich (1980), I distinguish the responses as follows:

Table 2. Possible responses to carbon dioxide issue.

	additional CO_2 generation	limit additional CO_2 generation
national response:	adaptation	abatement
international response:	compensation	prevention

Meyer-Abich describes the strategies as differing in the level of response and payment. Because climate is international, adequate preventive or compensatory countermeasures against climatic changes must be internationally coordinated, while programs below the international level can be only piecemeal reactions and appear more suitably to take the form of adaptation. However, it is not yet clear to what degree effective prevention must be international, nor is it clear to what extent abatement, or deduction from the full amount, which can be undertaken nationally, may make a noticeable contribution.

Meyer-Abich points out that there are a couple of basic characteristics to the selection of a response to climatic change. One is that the different involved parties, especially in international relations, usually do not agree on common goals, so that decisions requiring the least marginal action, or least change in behavior, tend to be favored. This situation suggests a structural bias in favor of adaptation. The other is that possible national activities for the various responses will be different, so that countries face essentially different decisions sets. In particular, some countries may find the prevention, abatement, and even compensation options irrelevant in practice and may only face the questions of whether and how to adapt. Meyer-Abich also points out that the options are connected with quite different time scales, as restriction of emissions by its very nature has to take place much earlier than compensation, which in turn likely precedes many adaptive measures. This feature leads to a further structural bias in favor of adaptation.

Meyer-Abich argues that there are two further reasons that prevention is unlikely. One is that there are already strong national incentives to reduce the consumption of fossil fuels, and that if these do not convince people to conserve or shift to non-carbon fuels, it is unlikely that prospects of a climatic change will. The second is that few changes are to the disadvantage of everybody. There are likely to be quite a few countries who stand to benefit from the change, and this will make CO_2 a political issue of a distributive nature, and such issues are not likely to be resolved by consensual international action. Similarly, a compensatory strategy is not likely to be decided in favor of, because the benefit of such programs is not well enough defined.

However, Meyer-Abich concludes only that prevention should not be expected if it comes at a considerable price. To the extent that CO_2 induced changes can be forestalled by way of a joint production of benefits with measures which are accepted for other reasons, preventive measures may be expected. For example, a strategy of reducing oil consumption, and thereby perhaps both imports and CO_2 emissions at the same time, may be a case of joint production of benefits for certain countries. Abatement may be characterized in a similar way.

Glantz (1979) has also argued against the likelihood of successful regulatory action on CO_2. Glantz argues that in general political decision-making has not been very effective in dealing with low-level cumulative environmental problems. While the political process is well-geared for coping with the spectacular impact of natural disasters which are sudden or in the form of "events," those which are a long-term process tend to find interest repeatedly dissipating even as the seriousness of the problem may be growing. Thus, we find societies coping relatively well with earthquakes, but not so well in respect to urban air pollution, and perhaps quite out of proportion to the risks associated with each. Glantz is certainly right that the diffuseness of the CO_2 issue through time is a strong argument against the likelihood of regulation, but the arguments about the diffuseness in space may not be as a cogent.

One of the arguments against the possibility of regulation most often presented is based on a picture of what the future sources of CO_2 will be. Rotty (1979) constructed the following figure (see also Figure 7, p. 30):

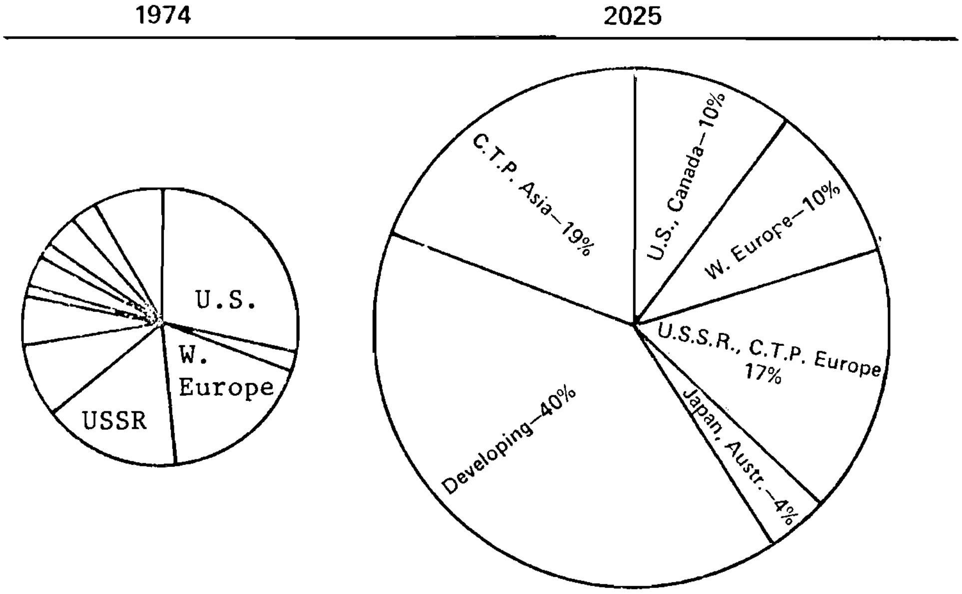


Figure 4. Global CO_2 production by world segments

The growing balance of the sources could lead one to be very pessimistic about regulation.

Because the industrialized world already has a substantial investment in fossil systems, it is not surprising to find Rotty (1978) concluding that

> ...analysis suggests that a major portion of the problem of avoiding the CO_2-triggered climate change is that of providing suitable energy alternatives (non-fossil) for the developing countries. Assuring progress of developing nations is an area in which the developed world should assign a high priority by emphasizing research and development on new, appropriate energy supply systems, e.g., small (decentralized) non-fossil systems.

While this may be an intelligent international development strategy, we shall see that a program which implicitly places significant responsibility for CO_2 increases on developing countries is probably inequitable from the point of view of the physical origins of CO_2, Rotty's pie chart notwithstanding. The reason for this lies in the fact that most authors have been looking only at figures of what countries might burn. They have looked primarily at the flow of CO_2 to the atmosphere, not at the equally crucially holdings of carbon wealth.

The carbon stocks of nations may tell a different tale with respect to the possibility and fairness of the responses we have identified. Rotty follows the previous statement with the following remarks:

> One might suspect that growth to 1,090 quads (or 23 x 10^9 tons of carbon) for A.D. 2025 will heavily tax the fossil fuel reserves of the world. This is simply not true; recoverable fossil fuels (and shale oil) contain 7.3 x 10^{12} tons of carbon.

In fact as we shall see, the carbon which could lead to a very serious CO_2 scenario over the next couple of generations will be extracted by a small number of countries, and these are, with one major exception, the advanced industrialized countries. If CO_2 is to be regarded as a global issue, it is largely because of trade in carbon and consequences of climatic change, not because of who owns the carbon stocks. But this future carbon economy is not the oil trade we know today.

Who then has been responsible for past emissions of CO_2, and who holds stocks for future exploitation? We shall look first at the biosphere and then at fossil carbon. With respect to past emissions, we shall examine combustion. It would also be interesting to see who has extracted the carbon from the ground, but we have not yet assembled statistics for that information. For the future we examine the stocks of carbon wealth in or on the ground, rather than projected fuel consumption, which is what is usually done. With respect to deforestation there is less of a difference between carbon extraction and combustion, because land-clearing and associated effects are not mediated by extensive trade the way extraction and combustion of fossil fuels may be.

To get a sense of the dimensions of the carbon economy needed to bring about a serious CO_2 problem, I will use the model proposed by Revelle and Munk (NAS 1977). According to their calculations between the period of 2040 when 1047 Gt of carbon may have undergone combustion and 2060 when 1581 Gt of carbon may have undergone combustion, a doubling of atmosphere CO_2 will have occurred. (See Table 3) As a convenient benchmark, let us say hypothetically that for CO_2 to be an urgent problem, a cumulative production of 1500 gigatons of carbon is required by the year 2050. This hypothesis presupposes a certain attitude towards the role of man in nature and the validity of a certain kind of methodology of impact assessment. The deeper issue raised by CO_2 may be whether people are relating themselves to nature in a responsible way, and not exactly how many degrees the temperature will rise or how much climatic change will cost in new irrigation works, but these questions are largely beyond the scope of this paper. (See Meyer/Abich 1979) Instead, let us try to work from some sort of simple imaginary linear picture of thresholds of seriousness of a CO_2 problem as measured by quantity and rate of emissions. (See Figure 5)

Table 3. Hypothetical carbon economy to 2140.

	Gt of Carbon			
Year	a) Cumulative fossil fuel production	b) Cumulative land clearing production	Total carbon wealth consumed (a + b)	Carbon added to atmosphere
1860	0	0	0	0
1950	62	42	103	43
1960	84	54	139	58
1970	115	70	185	76
1980	155	88	243	100
2000	279	131	410	171
2020	489	177	666	286
2040	827	220	1047	471
2060	1328	253	1581	750
2080	1987	271	2262	1123
2100	2730	289	3019	1540
2120	3432	298	3730	1908
2140	3997	302	4299	2154

SOURCE: After Revelle and Munk (NAS 1977:155).

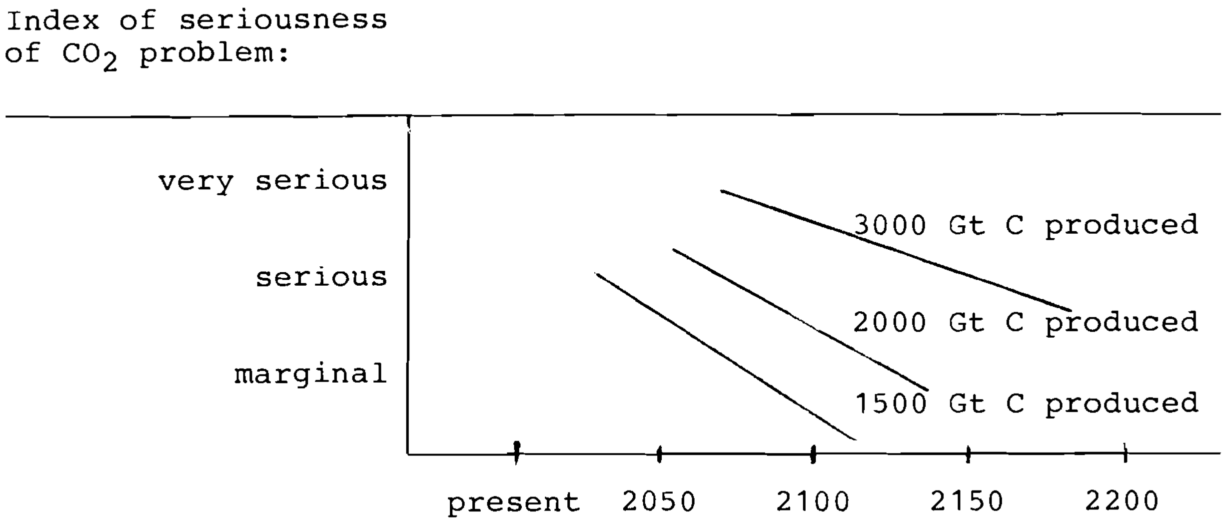


Figure 5. Hypothetical thresholds of seriousness of a CO_2 problem.

Biospheric Carbon Wealth

In this section we will look briefly at the regional origins of past possible cumulated flux of carbon from the biosphere to the atmosphere, at the distribution of possible present annual flux, and at stocks of biospheric carbon wealth which might in the future be consumed and converted to CO_2. We have seen that from a scientific point of view the biospheric controversy is significant in identifying the carbon cycle and the timing of possible climatic change. Is it important with respect to potential societal responses to CO_2? That is, do the liability for past contributions and the potential for future contributions (or withdrawals) of carbon dioxide have important implications for selection of a strategy of prevention, compensation, mitigation, or adaptation? First let us look briefly at the functioning of the biospheric carbon economy.

Human activity has modified the role of the biosphere in the carbon cycle, but in what direction and to what extent are much debated. Deposits and withdrawals of carbon in the biosphere can be made in a number of ways. On the debit side one finds, above all, burning for agriculture and for forest clearing, as well as industrial use of wood and removals of wood for fuel (firewood). In addition, withdrawal occurs through soil organic matter decomposition. On the asset side one finds reforestation, regrowth, and possible stimulation of growth by increasing atmospheric levels of CO_2 and NO_x. It is clear that forests play a dominant role. As Baumgartner (1979) has written, "Land use changes due to afforestation or deforestation are...very aggressive anthropogenic actions." Lieth (1974) has calculated that forests contribute 65% of the photosynthetic production of plant matter on land. In addition, forests have the highest rate of productivity, exceeding the productivity of cultivated land by 1 to 3 times, of grassland 2 times, and of the oceans up to 10 times. 82% of the phytomass may be categorized as being in forests (Bramryd, in Bolin et al. 1979:185), and forests are said to account for 49% of primary production. Baumgartner (1979) estimates that 42% of biospheric assimilation of CO_2 is performed by forests. The figures on forest area and production are extremely difficult to estimate and verify, but the preeminent role of forests in the biospheric carbon cycle is clear.

The nature of deforestation and the kind of forest being removed is significant. When clearing operations, particularly by burning, lead to complete removal, the amount of carbon released per area is comparatively large. However, much vegetation destruction moves more slowly. Moreover, there is a close relation between climate and the rate and form in which carbon is accumulated. In tropical areas, extensive regrowth can occur very quickly. In temperate regions, in spite of intensive logging, annual gains in phytomass may still outweigh the losses due to harvesting and industrial processing of wood. In contrast, due to slow plant growth, it is hard to see the northerly boreal zone playing a significant role as a sink on the time scales we are discussing. Still, in many countries of the world total wood production may have increased because of use of fertilizers, draining of swamps, and rationalization of production (Bramryd, in Bolin et al. 1979:187).

There is also a relationship between the forest humus and the climate. As Hampicke points out (in Bolin et al. 1979:164), the total amount of carbon accumulated in different forests in the form of soil organic matter, live phytomass, and dead phytomass may be approximately the same. However, in cold and temperate climates the accumulation takes place in the form of humus, while in tropical forests the largest amount of carbon is found in the form of living phytomass, mainly wood, and only a small amount in the form of litter. "Consequently, the clearing of tropical forests diminishes accumulated carbon more rapidly than in temperate forests. Moreover, an extra diminishing of carbon takes place through increased decomposition of soil organic matter after clearing, particularly in tropical areas." In general, the spread of agriculture to formerly uncultivated areas is likely to be significant in decomposition of soil organic matter, while intensification of cropping on soil already under cultivation, the more common phenomenon in industrialized countries, does not necessarily lead to further losses of humus.

What then is the history of non-fossil carbon? There is a great deal of disagreement about the cumulated flux. Keeling and Bacastow (1977) have calculated that there was a net increase of 28 Gt C in the biosphere, while Wagener (see Hampicke in Bach 1979:143) has estimated a net decrease of 208 Gt C, in the time since the beginning of extensive use of fossil fuels in the 19th century. To get a rough idea of the past exploitation of biospheric carbon wealth, I will analyze the figure for cumulative gross release from forest clearing and soil organic matter decay estimated by Revelle and Munk (1977), as this number seems to fall somewhere in the middle of the estimates.

According to Revelle and Munk, the total quantity of organic material in the biosphere has remained relatively constant since 1860. The release of carbon to the atmosphere by land clearing has been almost exactly balanced by the increase in the net photosynthetic production and storage of organic material resulting from the higher CO_2 content. The total gross loss of carbon to the atmosphere resulting from land clearing is about 75 Gt between 1860 and 1970, of which about 50 Gt were removed by the actual clearing and the remaining 25 Gt by changing the content of soil humus. Revelle and Munk arrive at their estimates on the basis of a region by region analysis of changing land cultivation, which makes their study particularly suitable for our purposes.

Combining regional land clearing statistics with estimates of characteristics of standing biomass, Revelle and Munk arrive at estimated original biomass categories of land cleared between 1860 and 1970. These are broken down according to carbon contributions by biome. By multiplying out the regional areas by the estimates of carbon in the biomass and adjusting for the admittedly arbitrary suggested loss of 30 tons per hectare in the average humus content, one can arrive at an estimate of total loss of carbon from the biosphere to the atmosphere resulting from land clearing between 1860 and 1970, according to region (see Table 4). Clearly, there is great uncertainty associated with these numbers, but they are suggestive from an economic and political point of view.

First, it is often said that deforestation is mainly a phenomenon of the developing countries. That may be true at present and into the future, but as far as historic biospheric contribution to the CO_2 issue goes, we estimate that more than 30 Gt out of the hypothesized 75 Gt, or over 40%, of gross biospheric contribution to the atmosphere over the recent period may have come from North America, Europe, the USSR, Australia, and New Zealand. Moreover, as Hampicke points out, "In industrial countries, substantial losses of soil organic matter were caused by cultivation in earlier periods of history..." (in Bolin et al. 1979:224). Indeed, in Europe, forests were in a particularly poor condition up to the 19th century, and since then there has been some recovery (Hampicke, in Bach 1979:150). Thus, it should be fair to state that to 1970, the biospheric contributions of industrial and developing countries were not grossly unequal.

Nonetheless, what is most striking is that the numbers involved are small. Compared to the "need" for a net contribution of 1500 Gt by 2050, the past biospheric contribution is quite minor, even if the figure of 70 is net, and even if it is off by a factor of 2. If, just as a thought exercise, we were to double these numbers and regard them as net, the historic contribution by any one region would still not be much more than 2% of our suggested "threshold" problem. Thus, past exploitation of biosperic carbon wealth does not appear to be of much significance with respect to arriving at just societal responses to the CO_2 question.

Table 4. Very rough estimates of total loss of carbon from biosphere to atmosphere resulting from clearing, 1860-1970, by region.

Region	Tropical Rain Forest	Tropical Seasonal Forest	Temperate Evergreen Forest	Temperate Deciduous Forest	Boreal Forest	Woodland and Scrubland	Savanna	Grassland	Swamp and Marsh	Totals
Northern America	-	-	3.8	4.2	1.2	-		4.6		13.8
Europe	-	-	-	1.8	-	-		.4	1.0	3.2
Soviet Union	-	-	7.5	-	2.4	-	-	5	-	14.9
Australia and New Zealand	-	-	-	1.3	-	-	-	.3	-	1.6
Africa S. of Sahara	3.5	2.9	-	-	-	2.9	2.4	-	-	11.7
Latin America	3.5	3.0	-	-	-	2.1	1.7	-	-	10.3
China	-	-	-	-	-	.3	.2	.1	.2	.8
Other Asia	3.5	9.4	-	-	-	4.1	1.9	-	-	18.9
Totals (Gt)	10.5	15.3	3.3	7.3	3.6	9.4	6.2	10.4	1.2	75.2

(Estimated original biomass in millions of hectares of cleared land 1860-1970 x carbon in biomass, tons/hectare) + decrease in average humus content of 30 tons per hectare = estimated total carbon loss from biomass, including soil, by region in Gt

Let us now take a sample estimate of current flux of carbon to the atmosphere from the land biota, and analyze briefly in accord with the geographical considerations. Hampicke offers the following summary of biospheric carbon use:

Table 5. Man-made transfer of carbon to the atmosphere from the land biota.

Activity	10^{15} g C/year
Forest clearing in the Third World	+3.6
Industrial use of wood	+0.3
Firewood	+0.3
Soil-organic matter decomposition	+0.6
Reforestation	−0.3
Regrowth in the tropics	−1.0
Regrowth in temperate regions	−0.5
Growth stimulation by CO_2	−0.3
Growth stimulation by NO_x	−0.2
Sum	+2.5

SOURCE: from Hampicke (in Bolin et al. 1979:230)

Forest clearing, fuelwood, and loss of soil organic matter would largely be taking place in the developing countries, evidently led by South America, but with sizeable activity in Africa and Asia, probably South and Southeast Asia. On the positive side, the most rapid regrowth is also in the tropics. A substantial portion of the growth stimulation might also be attributed to developing areas, if one allows a large net biospheric contribution. Working from Hampicke's estimates, one might estimate very roughly a net contribution of 3-4 Gt of carbon coming from developing countries at present. The developed countries are debtors with respect to pulp and other industrial uses of wood, but probably net out positively because of regrowth and their contribution to growth stimulation through emissions from fossil fuels. But, as with the historic contribution, all the numbers are small when compared to projected annual injections of 15 to 30 Gt C or to the need for an eventual contribution of 1500 Gt by 2050.

The question of future potential biospheric carbon exploitation remains. It should be noted that there is a symmetry between this question and the question of possible biospheric carbon uptake, as to a considerable extent the same geographical areas would be under consideration. Most future photosynthetic production and potential increases should occur in the forest areas remaining after land clearing.

From Hampicke (1980) we have estimates of carbon wealth categorized by vegetation unit (see Table 6).

Table 6. Present organic carbon stored in major land ecosystems in Gt C.

Vegetation Unit	Living phytomass 1977	Humus 1977
Tropical zone		
Moist forest	245.3	192.0
Dry forest and woodland	23.6	24.2
Grassland and bushland	42.0	79.8
Cultivated land	3.4	62.0
Swamp	10.1	45.0
Total	324.4	403.2
Temperate zone		
Forest and woodland	115.9	131.6
Wet grassland (meadow)	4.7	94.5
Dry grassland (steppe)	4.4	141.8
Cultivated land	3.2	60.0
Swamp	1.7	15.0
Total	129.9	442.8
Boreal zone		
Closed forest	73.1	133.9
Forest tundra	19.1	51.5
Tundra	5.7	163.2
Bog	3.4	105.0
Total	101.4	453.6
Semidesert	7.4	121.8
Extreme desert	0.4	1.8
Ice covered	0.0	0.0
Land total	563.5	1,423.2

SOURCE: After Hampicke (1980).

Let us first look at the question of dead organic matter, which Hampicke estimates as humus, but also would include standing dead organic matter, litter and litterfall, peat, as well as the organic matter accumulated in the soil as humus. This is not a very flexible sink for carbon, in spite of the large quantity stored. Neither is it a source that is subject to much intentional manipulation. As has been pointed out, there is a decrease in humus content of recently cleared land, and there may be a varying rate of exploitation of litter, but neither of these quantities is likely to be on a scale of more than tens of Gt of carbon. In contrast, some peat areas may be exploitable to a significant extent. Ajtay et al. (in Bolin et al. 1979:153) cite 165 Gt C as a minimum global value for exploitable peat. Such total exploitation of peat resources in the next 50 to 100 years is extremely unlikely. Thus, we may consider this reservoir as of small importance in the next century of the carbon economy.

In order to examine the potential of living organic matter, let us complement Hampicke's estimate of stocks with a table for annual flow of carbon into the biosphere. From Ajtay et al. we have an estimate of primary productivity by ecosystem type (see Table 7).

Clearly forest and tropical zones are potentially most significant within the biosphere to the global carbon cycle. We can estimate from Hampicke that 58% of the total living phytomass of land is in the tropical zone, followed by the temperate zone with 23%, and the boreal zone with 18%. Over 80% of the living phytomass is in forest and woodland. Of total primary productivity, forests account for 37% and savannas 30%. The forests of the world are not evenly distributed from the standpoint of ecological geography, with roughly 56% in the tropics, 24% in the temperate areas, and 19% in the boreal zone. Neither are they evenly distributed from the point of view of regions or political geography (see Table 8).

While the table shows the preeminence of the forest carbon wealth of South America, it also suggests important roles for North America and the USSR. To analyze this question, we must look at the uses of the forests. Cutting of forests for timber is largely a shift in the place of carbon storage. The carbon remains out of the biogeochemical circulation on time scales of interest to us. In contrast, wood used for fuel will be converted rapidly to CO_2, and wood used for pulp and paper production is also converted rather rapidly. Cutting of pulp wood is concentrated in the developed world, while use of firewood is largely a phenomenon of developing countries. It should be noted that Seiler and Crutzen (1980) propose an inert sink of charcoal for much burned wood. This includes the potentially largest source of carbon from the biosphere, the clearing of tropical forests by fire.

Table 7. Net primary productivity of terrestrial ecosystems of the biosphere.

Ecosystem type	Gt C net primary productivity
1. Forests	21.9
Tropical humid	10.35
Tropical seasonal	3.24
Mangrove	0.14
Temperate evergreen/conif.	2.02
Temperate deciduous/mixed	1.76
Boreal coniferous (closed)	2.49
Boreal coniferous (open)	0.73
Forest plantations	1.18
2. Temperate woodlands (various)	1.35
3. Chaparral, maquis, brushland	0.9
4. Savanna	17.71
Low tree/shrub savanna	5.67
Grass dominated savanna	6.21
Dry savanna thorn forest	2.05
Dry thorny shrubs	3.78
5. Temperated grassland	4.39
Temperated moist grassland	2.7
Temperated dry grassland	1.69
6. Tundra arctic/alpine	0.95
Polar desert	0.02
High arctic/alpine	0.24
Low arctic/alpine	0.69
7. Desert and semidesert scrub	1.35
Scrub dominated	0.81
Irreversible degraded	0.54
8. Extreme deserts	0.06
Sandy hot and dry	0.04
Sandy cold and dry	0.02
9. Perpetual ice	0
10. Lakes and streams	0.36
11. Swamps and Marshes	3.26
Temperate	0.56
Tropical	2.7
12. Bogs, unexploited peatlands	0.68
13. Cultivated land	6.77
Temperate annuals	3.24
Temperate perennials	0.34
Tropical annuals	2.83
Tropical perennials	0.36
14. Human area	0.18
TOTAL	59.9

SOURCE: After Ajtay et al., in Bolin et al. 1979:144-5.

Table 8. Amount of stem wood in the forests of the world.

Region	Amount of Wood in 10^9 m^3	%
Africa	39.0	12
America, North	58.5	17
America, South & Central	101.1	30
Asia, Pacific	48.5	15
Europe	12.8	4
U.S.S.R.	78.9	23
World	338.8	101

SOURCE: After Skogsstyrelsen 1976, in Bolin et al. 1979:188.

In any case, let us look at a few calculations of what biospheric carbon wealth may be convertible to atmospheric CO_2. While the overall amount of carbon in living biomass is equal to about one-third of our proposed threshold of a serious CO_2 problem, clearly much less than this will be consumed in coming generations. With respect to developed countries, Bramryd (in Bolin et al. 1979:194) offers two interesting figures. One is that the pool of carbon in above ground parts of standing trees in the USSR is about 9.16 Gt. Bramryd also roughly estimates the total carbon pool in the trees in North America at 7.31 Gt. Thus, it would appear that the greatest developed forest carbon powers do not have the capacity to play a significant role through the biospheric carbon economy in creating a serious CO_2 problem, especially given the current manner of exploitation of their forests. What about tropical carbon?

One suggestive calculation is the amount of carbon in the Amazon (see Bramryd in Bolin et al. 1979:198). Sioli estimated that the Amazonian forest contains about 600 tons of organic matter per hectare, or 30 x 10^3 gC/m^2. When one multiplies by an estimated area of 4 million km^2, the result is 120 Gt of carbon for the whole Amazonian forest. Such an amount is approximately equal to 8% of the proposed threshold for a CO_2 problem. Baumgartner (1979) performs a similar calculation to estimate the consequences of destruction of all the tropical forests, with a certain portion burned:

> The tropical forests of about 20 million km^2 with a growing stock of about 10^{12} t of dry biomass above the ground, are being destroyed at an annual rate of 0.3 million km^2. If at least one third of the dry matter is burnt or decomposed, about 4×10^{11} t O_2 will be used... and about 5.0×10^{11} t CO_2 (about 140 Gt C), or one fifth of the atmospheric CO_2 storage, will be released into the atmosphere.

Revelle (1977:145), looking at all biospheric sources, not just the Amazon or tropical forests, argues that the maximum future addition of CO_2 from land-clearing is about 240 Gt. These three estimates would appear to be consistent.

Given the range of estimates of historic contributions and presently available biospheric carbon stocks, it appears that the maximum feasible exploitation of carbon in the biosphere toward a CO_2 problem scenario in the year 2050 is in the range of 10% to 20%, if we allow vast combustion of forests and peat. In the most extreme scenario, we might find the Amazonian nations, given high estimates of past contribution and total future deforestation, accounting for 10% of the CO_2 problem. This appears to be the only clearly identifiable chunk of significant available carbon wealth in the biosphere. Any other individual store, whether the boreal forests and peat of Canada and the Soviet Union, or the tropical forests of Africa or Southeast Asia are not likely to account for more than a few percent. From the point of view of the well-being of developing countries, deforestation is a major issue, but from the point of view of their role in the CO_2 question, it is a minor one, with one exception. Total deforestation would be devastating to many countries from the point of view of national and perhaps regional preservation of soil, water, fuel, and other resources, but it would not constitute a large, long-term threat to the global atmospheric common.

As Hampicke (1980) has written:

> Any CO_2 quantity released from biotic sources in the future will be insignificant for the future atmospheric CO_2 level if fossil fuels will be consumed in large amounts. Biotic releases will be significant in a low-fossil-fuel scenario, however. If mankind should succeed in limiting the future use of fossil fuels, an additional effort to control the biotic sources would be fruitful. Likewise, biotic sinks such as reforestation will become relevant only in a low-fossil-fuel scenario.

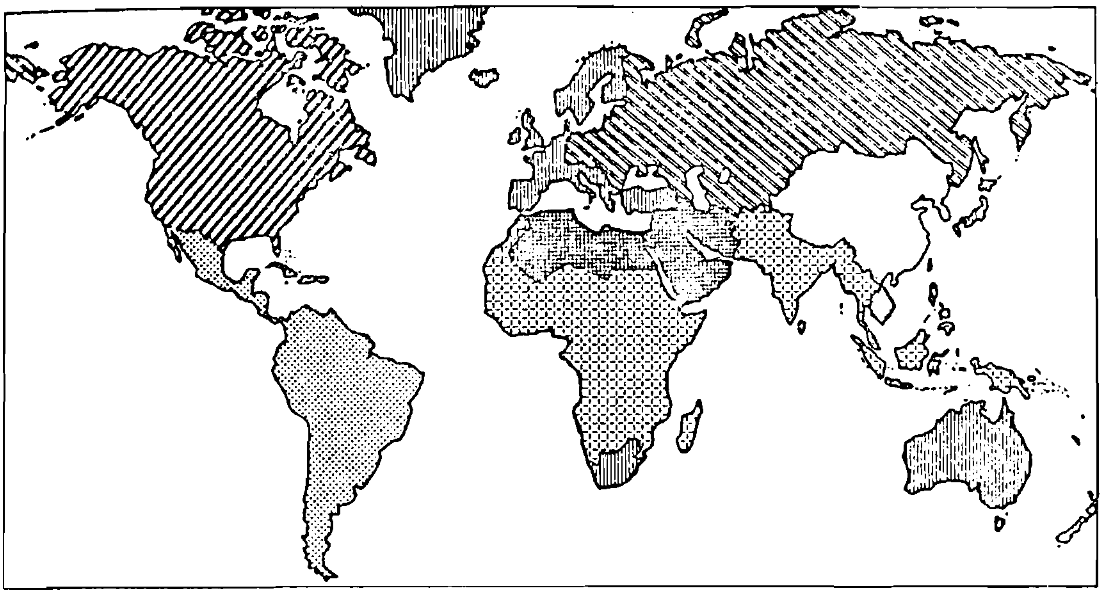
We might conclude with a few comments in reference to the four possible societal responses described earlier. It appears that efforts at restriction of biospheric emissions at the national level, or abatement, are unlikely to be effective. A few nations, like Brazil or the USSR, might undertake efforts at the national level which would be noticeable, but most nations will not be in a position to do so. An internationally coordinated effort at restriction of biospheric emissions, or prevention, could, as Hampicke notes, play a fruitful role just at the margin of a CO_2 problem. Similarly, international efforts to absorb additional emissions, or compensation, could be significant at the margin. However, in both cases reasons given earlier in the paper for pessimism about the possibility of control, for example, the physical diffuseness of the problem and the lack of international authority, lead one to believe that both of these are unlikely with respect to the biosphere, at least if action is motivated exclusively by concern about carbon dioxide. Thus, the structure of biospheric carbon wealth corroborates what many have been suggesting, that adaptation looks to be the most likely option. Nevertheless, the relatively small size of the potential biospheric contribution makes it even more important to look carefully at the likelihood of exploitation of fossil carbon.

Fossil Carbon Wealth

Now, let us turn to the question of carbon wealth stored in fossil forms. From a scientific point of view the underground reservoirs are less complex than carbon in the biosphere, but again measurement is difficult, and estimates vary widely. As in the previous section, we shall examine historic and current contributions, as well as possible future ones. In the case of historic contribution, it is necessary to aggregate the various fossil fuels, while for the future it is possible to explore the potential role of each. The framework used is that of the world regions defined for the IIASA energy systems program (see Figure 6), and the data used is that on reserves and resources assembled for the IIASA WELMM accounting system (IIASA, Forthcoming).

Rotty (1979) has assembled data for global CO_2 production by world segments in 1974 (see Figure 7). We can see that North America, Western Europe, and Centrally Planned Europe including the USSR are responsible for nearly three-fourths of the global total fossil fuel CO_2.

By integrating back through time, it is estimated with carbon cycle models that about 140 Gt of carbon have been injected into the atmosphere by fossil fuels (Bolin 1979:11). If we extrapolate into the past using Rotty's estimate of current shares and adjusting for IIASA energy regions we find the following assessment of historic contribution (see Table 9). While the percentage contributions have undoubtedly fluctuated over the years, these estimates should not be drastically wrong. They may be biased low for the industrialized countries, since the share of energy consumption of the developing countries has been growing slowly. It is important to note that we are dealing with an amount equivalent to less than 10% of the responsibility for the hypothesized problem. It is also interesting that the calculation yields a contribution figure of 111 Gt for the industrialized world, or about 80% of the 140 Gt. This is only a little less than the figure proposed for total deforestation of the Amazon.



	Region I	(NA) North America
	Region II	(SU/EE) Soviet Union and Eastern Europe
	Region III	(WE/JANZ) Western Europe, Japan, Australia, New Zealand, S. Africa, and Israel
	Region IV	(LA) Latin America
	Region V	(Af/SEA) Africa (except Northern Africa and S. Africa), South and Southeast Asia
	Region VI	(ME/NAf) Middle East and Northern Africa
	Region VII	(C/CPA) China and Centrally Planned Asian Economies

Figure 6. World regions defined for use in IIASA Energy Systems Program.

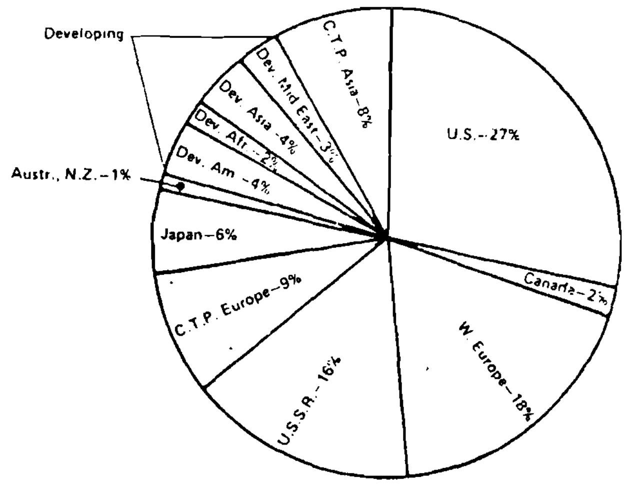


Figure 7. Global CO_2 production by world segments, 1974.
SOURCE: Rotty 1979.

Table 9. Assessment of historic contribution.

Region	I	II	III	IV	V	VI	VII
Percent in 1974	29	25	25	4	5*	4**	8
x total historic contribution (140)							
Regional contribution in Gt C***	41	35	35	6	7	6	11

* developing Africa & half developing Asia

** mid-East & half developing Africa

*** rounding error brings total to 141 Gt

Now let us turn in greater detail to prospective contributions, according to fuel and region. While current and past production data are obviously more reliable than data on what is in the ground, information on stocks is necessary to get an idea of the dimensions of fossil carbon wealth, and the likelihood of realization of a CO_2 problem. The IIASA WELMM approach to energy options has developed the complementary concepts of "reserves" and "resources" for categorizing mineral stocks. There is more of a difference between reserves and resources than a simple border line. The difference may almost be one of nature, not only of degree. The following figure gives some comments of comparison:

	RESERVES	RESOURCES
INTEREST IN ...	GREAT	NONE IN THE PAST, NOW EMERGING
TIME HORIZON	10 – 30 YEARS	LONG, OR VERY LONG TERM
ECONOMIC ASPECT	MUST BE PROFITABLE	NON-PROFITABLE TODAY, "SCIENCE FICTION" TECHNOLOGY
ESTIMATED BY	INDUSTRY	MEMBER OF INDUSTRY, OR GOVERNMENTS (INSTITUTIONS)
DATA	MORE OR LESS RELIABLE, CONSERVATIVE, "PROPRIETARY", AND EXPLOITATION-ORIENTED	UNCERTAIN OR SPECULATIVE, BUT SCIENTIFICALLY ORIENTED
METHODS	INDUSTRIAL WORK (EXPENSIVE): EXPLORATION, DRILLING, AND MEASUREMENTS	PAPER OR COMPUTER WORK: "GEOLOGICAL", "HISTORICAL"

Figure 8. Comparison of reserves versus resources.

For purposes of looking forward to the year 2050, the distinction between reserves and resources is an illuminating one. There is much higher probability of extraction associated with the reserves. If CO_2 is to become a problem, it will likely be because of a high rate of exploitation of reserves and more moderate encroachments on resources. Of course, these figures are not identical with what one might estimate specifically as "carbon exploitable to the year 2050," to which future research should be directed.

Using the data gathered in the WELMM framework for the IIASA Energy Systems Program, we now calculate fossil carbon wealth as represented in both more readily exploitable "reserves" and in longer-term, more uncertain "resources." For these calculations I follow the methods used by Rotty (1973), Keeling (1973), and Pearson and Pryor (1979). It may well be that the carbon fractions used here, particularly with respect to coal, are high. If the fractions are high, it will be necessary to recalculate to achieve more accurate estimates. However, unless the fractions are drastically wrong, the conclusions will not change much, as most of the carbon holdings are quite small and will only become more insignificant, while those which are large are so large that the reduction will not greatly reduce their significance anyway. Nonetheless, it should be clearly understood, that these are tentative estimates, subject to misestimation at several points, and designed primarily to open for discussion the topic of where and how a CO_2 problem may originate from the point of view of the physical resource. Individual tables by fossil fuel form and a summary table which displays estimates of historic contribution, potential reserve contribution, and potential resource contribution have been prepared (see Tables 10, 11, 12, 13, and 14).

Even allowing for great uncertainty, these tables offer an important basis for speculation about a CO_2 problem. First, we may note that the historic fossil contribution (about 140 Gt C) plus exploitation of all fossil reserves (about 540 Gt C), even with a maximum biospheric contribution (for example, 240 Gt C), will only be nearing two-thirds of the "needed" level of about 1500 Gt of carbon exploitation for a CO_2 problem. This figure, if correct, would have important implications for short term energy policy: no present investments need be abandoned on account of CO_2. Second, we may note that the sum of all oil and gas reserves and oil and gas resources seems to be less than 450 Gt C, a figure lower than one-third of our proposed threshold of danger. So, it seems that CO_2 is not a problem dominated or controlled by the oil and gas industries or nations. Indeed, if one sums the historic contribution, all reserves of all fuels (including coal) of all regions, maximum biospheric contribution, and all oil and gas <u>resources</u>, the total is still more than a couple of hundred Gt of carbon short of 1500 Gt. Even in the presence of intensive development of coal <u>reserves</u> then, exploitation of all oil and gas resources might <u>safely</u> proceed from the point of view of CO_2. Neither does CO_2 appear to be a problem from the point of view of developing regions, with one significant exception. If we aggregate the resources and reserves of all fuels of regions IV, V, VI, and even add the oil and gas of region VII (China et al.), only an amount in the area of one-third the threshold is reached.

Other interesting figures might be obtained from these estimates, but no matter how one approaches this tentative data, it is clear that CO_2 poses a problem overwhelmingly from one point of view: long-term, large-scale development of coal resources by a few regions, indeed, by a small number of countries within these regions. Unless these regions use up all their

Table 10. Preliminary estimate of carbon wealth in reserves and resources of oil. *

	Reserves		Resources	
Region	Oil (10^6t)	Carbon wealth (Gt)	Oil (10^6t)	Carbon wealth (Gt)
I	4,857	4.0	28,000	23
II	10,670	8.7	46,730	38
III	4,021	3.3	16,020	13
IV	5,521	4.5	23,000	19
V	6,176	5.1	21,150	17
VI	54,363	45	109,100	89
VII	2,736	2.2	12,730	10
Total	88,344	73	256,730	209

Oil (10^6t) x carbon fraction (.84) x fraction of carbon oxidized to CO_2 (.975) = total carbon in oil convertible to CO_2 (Gt)

Table 11. Preliminary estimate of carbon wealth in reserves and resources of gas. *

	Reserves		Resources	
Region	Gas (m^3 x 10^9)	Carbon wealth (Gt)	Gas (m^3 x 10^9)	Carbon wealth (Gt)
I	7,763	4.1	43,500	23
II	22,654	12	59,000	31
III	5,061	2.7	14,500	7.6
IV	2,695	1.4	15,000	7.9
V	3,560	1.9	12,000	6.3
VI	21,157	11	78,000	41
VII	594	0.3	10,000	5.3
Total	63,484	33	232,000	122

Gas (m^3 x 10^9) x carbon content (g/cm^2 540) x fraction of carbon oxidized to CO_2 (.97) = carbon in natural gas convertible to CO_2 (Gt)

*Calculations made to two significant figures, rounded.

Table 12. Preliminary estimate of carbon wealth in coal reserves.*

	Hard coal		Soft coal		All coal
Region	Coal (10^9tce)	Carbon wealth (Gt)	Coal (10^9tce)	Carbon wealth (Gt)	Total carbon wealth (Gt)
I	122	85	65	41	126
II	107	74	41	26	100
III	117	81	29	18	99
IV	4.9	3	5.9	4	7
V	43	30	1.9	1	31
VI	0.2	0.1	-	-	-
VII	99	69	n.a.	-	69
Total	493.1	342	142.8	90	432

Coal (10^9tce) x carbon fraction (.70 or .63) x fraction of carbon oxidized to CO_2 (.99) = total carbon in coal convertible to CO_2 (Gt)

Table 13. Preliminary estimate of carbon wealth in coal resources.*

	Hard coal		Soft coal		All coal
Region	Coal (10^9tce)	Carbon wealth (Gt)	Coal (10^9tce)	Carbon wealth (Gt)	Total carbon wealth (Gt)
I	1,286	890	1,400	870	1,760
II	4,127	2,900	892	560	3,500
III	683	470	80	50	520
IV	25	17	9.3	6	23
V	179	120	4.9	3	120
VI	0.4	0.3	-	-	-
VII	1,427	990	13.4	8	1,000
Total	7,727.4	5,400	2,399.6	1,500	6,900

Coal (10^9tce) x carbon fraction (.70 or .63) x fraction of carbon oxidized to CO_2 (.99) = total carbon in coal convertible to CO_2 (Gt)

*Calculations made to two significant figures, rounded.

Table 14. Summary of preliminary estimates of fossil carbon wealth by fuel and region in Gt.*

Historic Contribution

Fuel form/ Region	I	II	III	IV	V	VI	VII	World	World reserves plus resources
All fuels	41	35	35	6	7	6	11	141	n.a.

Carbon Wealth in Reserves in Gt

Fuel form/ Region	I	II	III	IV	V	VI	VII	World	World reserves plus resources
Coal	126	100	99	7	31	-	69	432	n.a.
Oil	4	9	3	5	5	45	2	73	n.a.
Gas	4	12	3	1	2	11	-	33	n.a.
Total reserves	134	121	105	13	38	66	71	538	n.a.
Total reserves + historic contribution	175	156	130	19	45	73	82	679	n.a.

Carbon Wealth in Resources in Gt

Fuel form/ Region	I	II	III	IV	V	VI	VII	World	World reserves plus resources
Coal	1,760	3,500	520	23	120	-	1,000	6,900	7,300
Oil	23	38	13	19	17	89	10	209	282
Gas	23	31	8	8	6	41	5	122	155
Approximate total resources all fuels	1,810	3,600	540	50	140	130	1,000	7,200	7,700
Approximate total reserves and resources	1,940	3,700	650	63	180	200	1,100	7,700	n.a.

Region I (NA) North America
Region II (SU/EE) Soviet Union and Eastern Europe
Region III (WE/JANZ) W. Europe, Japan, Australia, New Zealand, S. Africa, Israel
Region IV (LA) Latin America
Region V (Af/SEA) Africa (except N. Africa & S. Africa), S. & S.E. Asia
Region VI (ME/NAf) Middle East and Northern Africa
Region VII (C/CPA) China and Centrally Planned Asian Economies

*Figures rounded.

coal reserves and begin significant encroachment on their coal resources, it is not possible for the rest of the world, even under the most drastic scenarios, to do more than arrive at the bare margin of a CO_2 problem. Let us now look more closely at the possibilities for coal exploitation of the required dimensions.

The IIASA Energy Systems Program (ENP) explored the possibility for greatly extended use of coal in the 21st century. Let us look at one possible production and lifetime of global reserves. Using roughly assessed composite and aggregate limitations of water, manpower, transport, environmental safeguarding, and so forth, the ENP (Forthcoming) arrived at the following maximum production assumptions:

Table 15. Coal maximum production assumptions, high scenario (maximum annual domestic production constraint, GWyr/yr*)

Region	Base Year 1975	Year 1985	2000	2015	2030
I (NA)	559	900	1,500	2,000	2,700
II (SU/EE)	807	1,300	2,400	3,000	3,500
III (WE/JANZ)	466	600	800	1,000	1,000
V (Af/SEA)	116	225	450	825	1,315
VII (C/CPA)	325	800	1,500	2,000	3,500

*1 GWyr/yr = 1.08 x 10^6 tce per year.

The production of about 12,000 GWyr/yr of coal in 2030 should be equivalent to production of about 7 or 8 Gt C per year. If we make lifetime projections of use of coal reserves which are approximately in line with the constraints suggested above, we find possibilities like those on figure 9. The extraction of 640 10^9tce should be equivalent to production of 400-450 Gt C. It seems that this level of coal usage would be insufficient to bring about the levels of CO_2 and climatic change we suggested as a potential threshold. But before examining potentially larger amounts of coal extraction, let us look briefly at the implications of an amount like the one on figure 9.

First, let us examine the question of regional self-sufficiency in relation to regional resources. According to demands projected by the IIASA ENP, this should pose no great difficulties for the next 50 years, even under high energy scenarios, assuming those regions without vast coal resources (Regions IV, V, and VI) have alternatives.

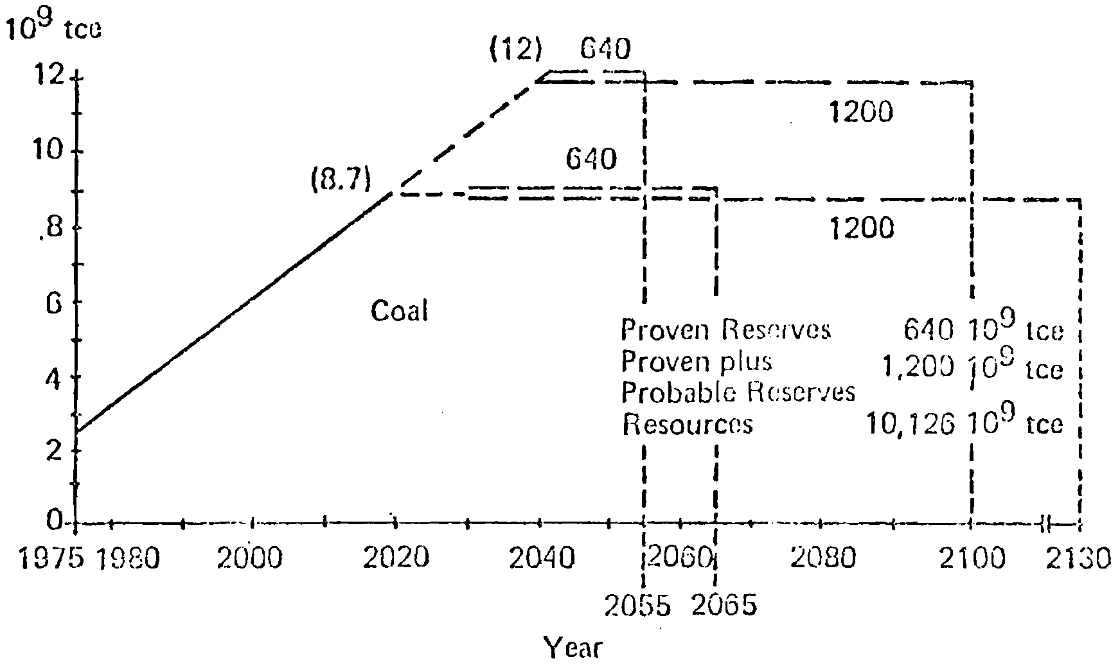


Figure 9. Coal: possible production and lifetime of global reserves. Solid line based on data from World Energy Conference (1978); dashed line is IIASA extrapolation.

> In Region I (NA), 46% in the High scenario (24% in the Low scenario) of the Category 1 [low cost coal] is consumed by 2030. Region III (WE/JANZ) uses nearly 50% of its Category 1 resource; if this region were to not import coal, use of domestic resources could reach 83%. The coal resource amount in Regions II (SU/EE) and V (Af/SEA) are also sufficient to easily avoid depletion, even in the High scenario, by 2030. Region VII (C/CPA), assumed to *not* enter the import market for energy in the next 50 years, faces the prospect in the scenarios of using much of its vast coal resource for domestic growth. In the High scenario, nearly all of its Category 1 coal is exhausted; yet all of its higher cost (up to $50/ton) Category 2 coal remains available after 2030. (IIASA, Forthcoming)

While the US, USSR, and China may for example, have fantastic coal resources, the range of answers to the question of rate of extraction may make an enormous difference. While from a simple carbon resource point of view, the quantities in question may be regionally plausible, the rate of extraction is not something one can so comfortably assume:

> For Region I, a ceiling of nearly 2.9 *billion tons per year* (2,700 Gwyr/yr) of coal production has been assumed--based on limitations of rail transport, water availability for Western U.S. surface mining, limited coal uses (*as* coal) within the U.S. and Canada, few deep water port facilities, and air quality and other environmental considerations.... Three billion tons of coal per year in the U.S. is an enormous mining activity; it is nearly five times the 1978 U.S. production rate. (For comparison, in the High scenario, the North America gross domestic product (GDP) grows by 3.75 times.) It is nearly twice the present coal mining of the whole world. It means great capital investments, large land uses, substantial numbers of new miners. Presumably it could be done.... (IIASA, Forthcoming)

Suffice it to say then, that it will be no easy job for societies from the point of view of technology or economy to produce 1500 Gt of carbon by 2050. It seems that the projections made in the past have not emphasized the practical geography of carbon. Of course, it is conceivable that all the scientific uncertainties in the carbon cycle and in atmospheric modeling will be resolved in such a way that smaller amounts of carbon are sufficient to bring about climatic change. If so, the margin of the problem may seem much more accessible than the discussion suggests so far with respect to both the biosphere and fossil fuels. However, let us suppose the opposite for a moment. Imagine the biosphere is a ready sink, that the atmospheric fraction is low, that the oceans can absorb a great deal of carbon dioxide and heat. Then is it conceivable that there will be a CO_2 problem? Is there a way we might produce 2000 or 2500 Gt of carbon within the next 100 or so years?

To produce this total level of carbon, we would need coal to supply approximately 1500 Gt, or an average of about 15 Gt C per year. The systems problems of producing and consuming 20 to 30 10^9 tce per year will be enormous. When one considers the present problems of mining, transporting, and converting roughly 2 10^9 tce per year, the difficulties of embedding tenfold or more larger technical operations in an increasingly populated world are most intimidating. The IIASA ENP has concluded with respect to a coal scenario about twice these dimensions that "local pollution and/or social conditions are likely to limit the deployment of coal on such a scale in those coal countries that have other energy options." The same may happen well before the CO_2 threshold can be reached.

There is a second major reason to doubt the feasibility of a high carbon scenario: international trade. Supposing our estimates of carbon wealth to be reliable, we can see that the only way for severe CO_2 crisis to come about is through a global coal market. While it might be possible to arrive at the margin of a CO_2 problem without truly dramatic interregional transfers, to go beyond this will require massive carbon trade. This carbon trade is hardly the oil trade of today. Coal resources and reserves are very unevenly distributed worldwide, and the coal rich nations are China, the USSR, and the USA, as can be seen from table 16. In addition to having the largest reserves, these countries are presently estimated to have about 87% of the world's total resources. As the report of the IIASA ENP (Forthcoming) points out,

> One major question relates to the possible supply role of the three coal giants (the USSR, the US, and China) which have tremendous resources but also very large domestic energy requirements. It is not clear whether these countries would be willing and/or able to manage additional capacity for an export market, although this may serve political or economical purposes. Potential customers could also be reluctant to increase their "energy dependence" on these political giants.

If we think back to Rotty's figure on future sources of CO_2 emissions, we find a strong contrast. The crucial issue in the long term is not the energy path of the developing countries, unless we foresee a massive trade in carbon (that is, coal) from the USSR, the US, and China to the developing (and other) countries. The crucial issue is whether the few countries with dangerously large carbon wealth will choose to exploit it. If it stays under the ground, it obviously will not undergo combustion, nor contribute to threatening figures of "projected fuel consumption."

Table 16. World distribution of Coal resources (in 10^9 tce).

Greater than 10^{12} tce ($1{,}000 \times 10^9$ tce)		Between 10^{11} and 10^{12} tce (100 and $1{,}000 \times 10^9$ tce)		Between 10^{10} and 10^{11} tce (10 and 100×10^9 tce)		Between 10^9 and 10^{10} tce (1 and 10×10^9 tce)	
USSR	4,860	Australia	262	India	57	GDR[a]	9.4
U.S.	2,570	FRG	247	South Africa	57	Japan	8.5
China	1,438	UK	163	Czechoslovakia	17.5	Columbia	8.3
		Poland	126	Yugoslavia[a]	10.9	Rhodesia	7.1
		Canada	115	Brazil	10	Mexico	5.5
		Botswana	100			Swaziland	5.0
						Chile	4.6
						Indonesia[a]	3.7
						Hungary[a]	3.5
						Turkey	3.3
						Netherlands	2.9
						France	2.3
						Spain	2.3
						North Korea	2
						Romania	1.8
						Bangla Desh	1.6
						Venezuela	1.6
						Peru	1

[a]Mostly lignite.
SOURCE: Based on data from World Energy Conference (1978).
(for a very rough estimate of carbon wealth in Gt, multiply by two-thirds.)

The finding that the CO_2 issue is essentially a long-range coal issue is not a new one. To illustrate the difficulties of choosing a dominant path for coal in a global energy strategy, the IIASA ENP (Williams et al. (1979) analyzed a very high comprehensive coal scenario up to the year 2100. The results showed that such a strategy would deplete the world's fossil resources and pour an imprudently large amount of carbon dioxide into the atmosphere. While it may be easy to recognize that in the long run, CO_2 is a limiting factor in development of coal resources, it has not been generally recognized that in fact the key decisions are, or will be, in the hands of a few actors. Nor has the possibility been widely discussed that characteristics of the earth's carbon resources, particularly with respect to international trade and technical feasibility of exploitation, may well prevent carbon dioxide from reaching threatening levels in the coming century.

Distributive Implications of Carbon Use and Climatic Change

From an economic point of view the optimal management of the atmosphere would be based on an identification of its highest value under alternative uses. It is unlikely that we will have a good picture for some time of the benefits and costs of the various uses of the atmosphere, both the current ones, which include the "production" of our present configuration of macro and micro climates, and other feasible ones. While it may be very difficult to achieve any allocation of uses of the atmosphere, particularly carbon waste disposal, according to efficiency criterion, it may be possible to arrive at a sketch of the situation with respect to equity or fair distribution of gains and losses. And from the point of view of selection of societal response to the CO_2 issue, that may be the outstanding consideration. Although there may be important distributional effects within a country, we will focus here on questions of effects among nations, as it is the international level which is currently the focus of much debate on distributive justice.

Net benefits of atmospheric use presumably accrue at present principally to the nations that exploit atmospheric services. Waste disposal in the air appears to be an especially "profitable" activity. This suggests that at least in the short run the greatest national beneficiaries of the CO_2 increase are those countries engaged in carbon extraction and/or combustion. The main losers, if any, will be those nations in which economic activity will be adversely affected by climatic change, and those, in case of a preventive strategy of climate conservation, who are left holding useless untransformed (underground) stocks of carbon.

Is it just for those favored by geographic endowment or technological capability to act unilaterally, that is, participate massively in the carbon economy, without being held accountable for consequences to other users of the atmosphere and its climatic attributes? Such actions may raise the price to others of access to preferred supplies, for example, through the need to shift agriculture to areas of better climate which lack infrastructure. Or, it may even use up those supplies, for example, by making temperate climates scarcer, or, it may degrade future supplies, for example, by leading to an increased variability of climate. The climate may in a sense be depleted by the activity of some countries, and "favorable climate," particularly for agriculture, may become increasingly valued in a world with adversely changing supply conditions and growing population and growing demands by that population. Scarcity tends to bring allocative regimes as resources are more intensively used.

It does not seem unlikely that those who cannot exploit the atmosphere as a carbon dump may seek to obtain rent from those who do, or may at least seek to share the benefits with them. Or, they may try to forestall use of the atmosphere's capacity for carbon, until they can develop their own capability for exploitation. The majority of nations are increasingly hesitant to accept international arrangements on entitlement to common property resources like the atmosphere without compensating payments.

Not only may there be international pressure against atmospheric CO_2 increases for the reasons of uneven spatial distribution of benefits, but as has been hinted there are intertemporal reasons as well. Arrow and Fisher (1974) and others have argued that cases involving irreversible changes, like CO_2, evoke an option value. The passage of time may result in new information about the costs and benefits of alternative behavior, and this knowledge may inform the eventual decision if the decision to develop or use has been deferred. In cases of irreversibility there is a positive option value to refraining from development. The significance of irreversibility is further heightened in the CO_2 case by the fact that the atmosphere is a global common: people will not be in a position to reject any consequences they do not like. The consequences will be spread arbitrarily and shared.

While it appears clear who the beneficiaries of a carbon economy are, can we guess about who are likely to be those who will not benefit or even suffer? First, we must caution that trying to see 70 or 100 years into the future is an extremely speculative exercise. The world will be very different. Indeed, it is impossible even to say with much confidence which countries will be rich and which countries poor. A climatic change may well be overwhelmed by other natural or socio-economic events. However, climatic change may also make a significant contribution to the difficulties of a highly stressed world. So, let us try to make a few generalizations about the probable pattern of effects.

One way to begin is to look at the present pattern of impacts of climate on societies. Of course, one can argue that a brief assessment of the impacts of short-term climatic hazards cannot be equated with the impacts of a long-term climatic change. There is a profound qualitative difference between a transient disaster and a permanent change integrated over a very long time. (Ausubel and Biswas 1980) However, as Czelnai (1980) points out, the impact of a slow and gradual climatic change on society and economy will probably appear in the shape of difficulties caused by the changing recurrence time of extreme values on which important designs may be based. Any assessment of long-term impacts, therefore, must be accompanied by study of the impacts of short-term variability. So, it may be that assessments of climatic hazards at least give us a general idea of where vulnerability to natural hazards is greatest, and how it is likely to manifest itself.

According to Kates (1979), at least three-quarters of the estimated $40 billion per year of global natural hazard costs originate from three prevailing features of climate: floods (40%), tropical cyclones (20%), and drought (15%). Of this monetary measure, about $25 billion are incurred as losses, and the remainder is spent in prevention and mitigation. It is also estimated that natural hazard claims the lives of about 250,000 persons per year. How are these losses of life and money distributed? Kates' research indicates that 95% of the deaths take place in the poorer nations, while 75% of the property losses occur in the wealthy countries. But, measuring costs as a proportion of GNP, one finds the costs again much heavier in developing countries. The following table offers some comparisons (see Table 17). Kates interprets the numbers this way:

> The absolute cost of drought in a wealthy nation such as Australia exceeds that of Tanzania thirty-fold, yet the impact on the national economy in terms of the proportion of GNP is reversed, with annual drought costs in Tanzania equivalent to 1.8% of GNP and 0.10% in Australia....

Kates concludes that in proportional terms expressed as GNP, climatic hazards have an impact on poor countries 20 to 30 times the rate on rich countries. And Kates goes on to say that the inequality of suffering persists within countries: landless laborers, old people, women and children were the major victims of the Bangladesh Cyclone of 1970, debt-ridden farmers in the Nigerian drought in 1972, marginal people in the Kenyan drought in 1969, and Indians in floods in the U.S.A. in 1972.

While it is only mildly persuasive to use variability as a scale for the impacts of climatic change, it does seem probable that the cost of climatic change to the US or USSR will be in money, not in lives, while in other parts of the world the reverse may well be true. Moreover, countries which are larger and have more varied internal geography and climate are more likely to be able to make internal adjustments. Smaller countries with more homogeneous geography are likely to be at greater risk (or benefit). So, it is plausible to argue that among the countries with much to gain from "production" of a carbon dioxide problem and much to insulate them from disastrous effects of climatic change are the US and USSR. Smaller, poorer, agrarian countries are probably most vulnerable.

Table 17. Selected estimates of natural hazard losses.

Hazard	Country	Total Pop.	Pop. at Risk	Annual Death Rate/ Million at Risk	Losses and Costs Per Capita at Risk			Total Costs as % of GNP
					Damages Losses	Costs of Loss Reduction	Total Costs	
Drought	Tanzania	13	12	40	$ .70	$ .80	$ 1.50	1.84
	Australia	13	1	0	24.00	19.00	43.00	0.10
Floods	Sri Lanka	13	3	5	13.40	1.60	15.00	2.13
	United States	207	25	2	40.00	8.00	48.00	0.11
Tropical Cyclone	Bangladesh	72	10	3000	3.00	.40	3.40	0.73
	United States	207	30	2	13.30	1.20	14.50	0.04

SOURCE: Kates (1979).

The CO_2 problem appears to be a fairly clear case of potential disproportionate use by a few coal rich countries, which are at present, with the significant exception of China, already the richer, more industrialized countries, of the international commons for waste disposal. As such, many countries, which to date have displayed small interest in the issue, may find that they, while standing to gain little from the carbon economy in its gross form of long-term coal exploitation, which is the sine qua non of a CO_2 problem, are at some risk, and distributive aspects of CO_2 may thus become an important issue. However, it is also possible, especially in a marginal CO_2 scenario with maximum biospheric contribution, that the exploiters of carbon will be widely enough spread that the question of national liability for climatic change remains secondary.

CONCLUSION

What can we conclude about the four possible societal responses to the CO_2 issue in light of the discussions of carbon wealth in this paper? First, it appears that the problem is not "inevitable" or "imminent" as some have assumed. Climatic change may never happen for reasons quite apart from intentional prevention, abatement, or compensation, but simply because the carbon is not easily available. Second, it appears that if a CO_2 problem is to occur, it is more likely to be at the lower end of the scale of seriousness. The 4x CO_2 world which some have been modeling may be interesting as basic research on the behavior of the physical climate system, but it does not seem relevant to the twenty-first century. Futures with an increase in CO_2 from 1000-1500 Gt C seem much more realistic on the basis of our assessment of distribution of carbon wealth. If the likelihood of the realization of the problem diminishes, this would seem to favor adaptation, for the reason Meyer-Abich (1980) offers, that it involves the least marginal action at present.

With respect to compensation, the ideas developed here do not change the situation. It remains a difficult path to follow because of the evidently limited capacity of the biosphere (or other sinks) and the need for widespread international cooperation to make an effort that would reach beyond a few tens of Gt of carbon.

In contrast, the choice of abatement or prevention may be considerably enhanced by the arguments here. As we have just seen, there may be distributive issues which could create international political pressure for stopping climatic change from taking place. Moreover, the capacity to regulate the problem in its gross form, and even at more delicate levels, seems greatly enhanced by our picture of the structure of the earth's carbon wealth. Prevention would probably not require cooperation among all nations, or even among many nations. Coordinated action by the three coal giants should suffice, and indeed it may be that at the margin action for abatement by one of the three could be important.

Given the scientific uncertainties about CO_2, the lack of knowledge about the economic and other consequences of increases in CO_2 and climatic change, and the lack of a structure for control and management of the atmosphere, both at the national and international levels, it is easy to join other writers on the subject and affirm that society will not come to grips with this question in a decisive way. Those best served by the present administration of the atmosphere are the heaviest users of it, namely those engaged in carbon economy. Political and economic domination of the world by these countries may enable them to proceed with easy disposal of their carbon residuals. However, if it turns out that we can rely on the tentative estimates presented here of the carbon wealth of the earth and its distribution among nations, there need never be a pressing CO_2 question, either because the earth has protected its carbon well, or because of the wise action of peoples.

REFERENCES

Ajtay, G.L., P. Ketner, and P. Duvigneaud (1979). Terrestrial Primary Production and Phytomass, in Bolin et al., 120-182.

American Association for the Advancement of Science (1979). Report of Workshop (Annapolis, April 1979) on Potential Consequences of Climate Change, Washington D.C.

Arrow, J. and A. Fisher (1974). Environmental Preservation, Uncertainty, and Irreversibility. Quarterly Journal of Economics LXXXVIII 2, 312-319.

Ausubel, J.H. and A.K. Biswas (eds.). Climatic Constraints and Human Activities, Pergamon, Oxford, Forthcoming.

Ausubel, J.H. Economics in the Air: An Introduction to Economic Issues of the Atmosphere and Climate, in Ausubel and Biswas (eds.), Forthcoming.

Ausubel, J.H. and A.K. Biswas. Introduction and Overview, in Ausubel and Biswas (eds.), Forthcoming.

Ayres, Robert U. (1979). Applications of the Materials-Energy Balance Principle: Resources, Environment, and Economics, New York, Wiley and Sons.

Bach, W., J. Pankrath, and W. Kellogg (eds.) (1979). Man's Impact on Climate, Elsevier, Amsterdam Oxford New York.

Baumgartner, A. (1979). Climatic Variability and Forestry, in WMO.

Bolin, B. (1979). Global Ecology and Man, in WMO.

Bolin, B., E.T. Degens, S. Kempe, P. Ketner (1979). The Global Carbon Cycle. SCOPE 13, John Wiley and Sons, Chichester, New York, Brisbane, and Toronto.

Bramryd, T. (1979). The Effects of Man on the Biogeochemical Cycle of Carbon in Terrestrial Ecosystems, in Bolin et al., 183-218.

Broecker, W.S., T. Takahashi, H.J. Simpson, and T.H. Peng (1979). Fate of Fossil-Fuel Carbon-Dioxide and the Global Carbon Budget. Science CCVI 4417, 409-418.

Cowling, C., P. Crutzen, G. Likens, R.M. Garrels, J. Perry, and S. Pirages (1980). Biogeochemical Circulation: Problem Definition and Approach. Climate Research Board, National Academy of Sciences, Washington D.C., Unpublished.

Czelnai, R. (1980). Climate and Society: Great Plain of the Danube Basin, in Ausubel and Biswas (eds.), Forthcoming.

Freyer, H.D. (1978). In Carbon Dioxide, Climate and Society, J. Williams (ed.), Pergamon, 69.

Glantz, M. (19 July 1979). A Political View of CO_2. Nature 280, 189-190.

Hampicke, U. (1979). Net Transfer of Carbon Between the Land Biota and the Atmosphere, Induced by Man, in Bolin et al., 219-236.

Hampicke, U. (1979). Man's Impact on the Earth's Vegetation Cover and its Effects on Carbon Cycle and Climate, in Bach et al. (eds.).

Hampicke, U. (1980). The Role of the Biosphere. AUGE University of Essen, Federal Republic of Germany, to be published.

IIASA. Energy in a Finite World: A Global Energy Systems Analysis. Energy Systems Program of the IIASA, W. Haefele Program Leader, Laxenburg, Austria, Forthcoming.

Kates, R.R. (1979). Climate and Society: Lessons from Recent Events, in WMO.

Keeling, C.D. (1973). Industrial Production of Carbon Dioxide from Fossil Fuels and Limestone. Tellus 25, 174.

Keeling, C.D. and R.B. Bacastow (1977). Impact of Industrial Gases on Climate, in National Academy of Sciences.

Kneese, A.V., R.U. Ayres, and R.C. d'Arge (1970). Economics and the Environment--A Materials Balance Approach, Baltimore, Johns Hopkins.

Kneese, A. and C. Schultze (1975). Pollution, Prices, and Public Policy. Resources for the Future, Baltimore, Johns Hopkins.

Lieth, W. (1974). Basis und Grenze für die Menschheitsentwicklung: Stoffproduktion der Pflanzen. Umschau, Frankfurt LXXIV 6, 169-174.

Manabe, S. and R. Wetherald (1979). Presented orally at AAAS Workshop, Annapolis.

Meyer-Abich, K.M. (1980). Chalk on the White Wall? On the Transformation of Climatological Facts into Political Facts, in Ausubel and Biswas (eds.), Forthcoming.

Meyer-Abich, K.M. (1980). Socioeconomic Impacts of Climatic Changes and the Chances of Alternative Political Responses--Prevention, Compensation and Adaptation. Climatic Change.

Meyer-Abich, K.M. Toward a Practical Philosophy of Nature. Environmental Ethics (Winter 1979) I 4, 293-308.

Munn, R.E. and L. Machta (1979). Human Activities That Affect Climate, in WMO.

National Academy of Sciences (1979). Carbon Dioxide and Climate: A Scientific Assessment, Washington, D.C.

National Academy of Sciences (1977). Energy and Climate, Washington, D.C.

Pearson, C. and A. Pryor (1979). Environment: North and South, An Economic Interpretation, John Wiley and Sons.

Revelle, R. and W. Munk (1977). The Carbon Dioxide Cycle and the Biosphere, in National Academy of Sciences.

Rotty, R.M. (1973). Commentary on an Extension of Calculative Procedure for CO_2 Production. Tellus 25, 508-517.

Rotty, R.M. (1979). Energy Demand and Global Climate Change, in Bach et al.

Rotty, R. (1978). Paper on Carbon Dioxide and Climate in Resources and Energy (Nov. 1978) I 3, North Holland, Amsterdam.

Rotty, R.M. (1979). Present and Future Production of CO_2 from Fossil Fuels--A Global Appraisal, in U.S. Dept. of Energy.

Sioli, H. (1973). Recent Human Activities in the Brazilian Amazon Region, in Meggers, B.J. et al. (eds). Tropical Forest Ecosystems in Africa and South America, Smithsonian Institute, Washington, D.C., 321-334.

Skogsstyrelsen (1976). Skogsstatistisk arsbok 1974. Sveriges Officiella Statistik, Skogsstyrelsen, Jonkoping.

Stuiver, M. (1978). Science 194, 253.

United States Dept. of Energy (1979). Report of the Workshop on the Global Effects of Carbon Dioxide from Fossil Fuels. Miami Beach, Florida (7-11 March 1977), Elliott, W.P. and L. Machta (eds.).

Williams, J. (ed.) (1978). Carbon Dioxide, Climate and Society. Pergamon, Oxford, England.

Williams, J., W. Haefele, and W. Sassin (1979). Energy and Climate: A Review with Emphasis on Global Interactions, in WMO.

Woodwell, G.M., R.H. Whittaker, W.A. Reiners, G.E. Likens, C.C. Delwiche, and D.B. Botkin (1978). The Biota and the World Carbon Budget. Science 199, 141.

World Energy Conference (1978). World Energy Resources 1985-2020: Coal Resources. An Appraisal of World Coal Resources and Their Future Availability. Guildford, UK, IPC Press.

World Meteorological Organization (WMO) (1979). Proceedings of the World Climate Conference, Geneva.