A COMPREHENSIVE PLAN FOR CARBON DIOXIDE EFFECTS RESEARCH AND ASSESSMENT

PART I: THE GLOBAL CARBON CYCLE AND CLIMATIC EFFECTS OF INCREASING CARBON DIOXIDE

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Preface

During 1976, the Energy Research and Development Administration (ERDA), now part of the Department of Energy (DOE), recognized the concern that the effects of increasing levels of atmospheric carbon dioxide from fossil fuel combustion might significantly alter the global environmental and social system. ERDA set out to determine the extent of the problem, the adequacy of the research programs addressing the problem, and the need for the Agency's involvement. A major workshop was held in March of 1977 in Miami Beach, Florida, to address these questions. The consensus of the Workshop was that the question was unprecedented in terms of potential for impact, and that the ongoing research activity was, in many areas, at much too low a level to furnish timely answers. It was also clear that no focus for this activity existed either nationally or internationally. At the time, the formation of the Department of Energy was imminent and it was this Department which would constitute the major national focus for energy policy development. For these reasons, and with the advice and encouragement of an advisory committee, the Study Group on the Global Effects of Carbon Dioxide, DOE moved ahead with the development of a program. An Office of Carbon Dioxide Effects Research and Assessment was formed to administer the program.

The first activity of the Office was the development of an institutional plan for implementing the program. The goal toward which the plan is directed is:

> "To develop the ability to predict the environmental, economic, social and political costs of increasing atmospheric concentrations of carbon dioxide with sufficient confidence to permit policy decisions to be made on the future global use of fossil fuels."

Three strategic approaches toward implementing the goal were developed. These are:

- To begin the creation of a national and international focus for the carbon dioxide effects issue.

- To act as a lever to insure adequate funding of the scientific community for the conduct of a highly coordinated, unprecedentedly interdisciplinary national and international research effort.

- To conduct the information synthesis and analyses required to provide predictions of societal costs required for policymaking and to determine mechanisms for increasing the confidence in those predictions.

These strategic approaches imply a variety of necessary actions in areas of institutionalization, planning and heightening awareness of the potentially unprecedented nature of the problem. The development of an action-oriented research plan to which all involved organizations could subscribe was regarded as a critical item to ". . . insure adequate funding. . ." and this regard was the genesis of the Plan which follows.

The Plan outlines, in order of priority, the first portion of an urgently required research effort; an effort which is incremental to ongoing activities throughout the world. The Department of Energy will be guided by this Plan in developing its research program and offers it to the governmental and scientific communities as a focus about which the required major national and international effort can be developed.

The DOE Carbon Dioxide Effects Research and Assessment Program as a whole is involved in many other activities, particularly those related to the management and internationalization of the program, to insure that the strategic approaches will be implemented and the goal reached expeditiously and economically.

While many individuals were involved in preparing this document and even more in discussions leading to the final version, we wish to single out Drs. Lester Machta and William Elliott of the Air Resources Laboratories, Environmental Research Laboratories, National Oceanic and Atmospheric Administration, for their truly outstanding efforts without which, literally, the development of the program would not have been possible.

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Executive Summary

The well-documented increase of carbon dioxide in the atmosphere has lead to concern about the impact on the world's climate. The National Academy of Sciences report, "Energy and Climate," states "The climatic effects of carbon dioxide release may be the primary limiting factor on energy production from fossil fuels over the next few centuries." To obtain answers to the many questions raised by this issue requires a research program of considerable magnitude and scope conducted over at least a decade. Presented here is an outline of some of the specific research needed to attack the problems. These problems are:

1. What will be the future atmospheric concentrations of CO_2?
2. What will be the climatic effect of these concentrations?
3. What will be the effect on the biological and physical environment of these climate changes coupled with the increases of CO_2?
4. What, if any, will be the effects of these changes on human societies?
5. In the event that these changes are undesirable, what actions can be taken to prevent them?

The research outlined in this document addresses mainly the first two questions because these are the first steps in defining the problems. The other questions will require similar efforts. It would not be wise to wait until definitive answers to the first questions are available before starting on the next set: it will take a very long time to find their solutions and work can be started soon on each aspect of the societal issue.

More space is devoted to carbon cycle problems than climate questions because these questions have received less discussion than climate problems. There are many discussions of climate research needs whereas only recently has the carbon cycle received similar treatment.

The program contains suggestions on priorities and rough estimates of required funding. Some choice will have to be made on the order of starting the work because large sums of money will probably not be available immediately. The estimated dollar levels (1977 dollars) are predicted on continued support at the present levels for much on-going work. The funding estimates represent additions to current levels.

The carbon cycle receives the most detailed attention. The goal of the program is to produce an integrated model of this cycle so that future atmospheric concentrations of CO_2 can be predicted. This will involve estimates of future sources from industrial activity and from man's influence on the biosphere, increased observation of the changes in atmospheric CO_2 concentration and greater understanding of the behavior of the oceanic and biospheric sinks.

There is a need for more detailed and reliable estimates of the climatic consequences of increased CO_2. Much work is presently going on with General Circulation Models and less sophisticated one- and two-dimensional models but improvements are needed. In particular, coupling of atmospheric and ocean models, and improved treatment of cloudiness and the cryosphere should improve the realism of predictions.

Reconstruction of past climates is useful to validate the computer simulations and to provide estimates of possible future climate.

Other questions of no less urgency were considered briefly. Further investigation of the specific research needs in these areas is recommended. They involve studies of the effects of changing climate on the biosphere, particularly agricultural systems, and on the physical world, particularly the polar ice sheets and the oceans.

The impacts of these possible changes in the environment on human society must be better understood. This will require the efforts of social and political scientists and economists as well as biologists, climatologists and oceanographers. One need not await resolution of the climatic, biological, and cryospheric changes; plausible future climate scenarios should be constructed now to study potential environmental consequences.

Finally, investigation of practicable ways of reducing the CO_2 content of the air, either by direct removal from the air or by "scrubbing" the effluent of power plants should be investigated. These may not be feasible but the world should know if technological solutions are or are not available to solve potential CO_2 problems.

In carbon cycle research this plan calls for immediate funding of:

- improved estimates of the industrial source term;
- use of the isotopes of carbon as clues to the contribution of the biosphere to recent changes in atmospheric CO_2;
- feasibility studies of directly determining future changes in both vegetation and soil carbon content;
- expansion of the observing network for atmospheric CO_2 concentrations, including the carbon isotopes.

- detailed planning for oceanographic surveys of transient tracers in the oceans. The full program should begin soon after the detailed plans are completed to assess the rate of transfer of carbon species from the surface water to the deeper oceans;

- investigation of the buffering of oceanic CO_2, including the possibility of shallow-water buffering by solids.

The next steps should include the following:

- determine the response of the biota to increasing CO_2;

- intensity efforts to construct models of the carbon cycle.

Following these, the next steps should be:

- refinement of the estimates of gas-exchange rate across the air-sea interface;

- determine the magnitude and importance of the organic fluxes of carbon into the ocean from rivers and within the ocean;

- improve the measurement techniques for atmospheric CO_2.

Finally, the carbon cycle program recommends:

- studies of the dissolution of the deep-ocean sediments as the final sink for atmospheric CO_2.

In the areas of improving climate prediction, immediate support should be provided to:

- develop a coupled ocean-atmosphere General Circulation Model.

Subsequent steps would be:

- improved treatment of the cryosphere and clouds;

- intensify efforts to reconstruct past climates.

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I. INTRODUCTION

This document outlines some of the research needed to answer questions raised about the environmental effects of increasing carbon dioxide concentrations in the atmosphere. It is an interim plan: it will be subject to change as knowledge increases and because not every facet of the problem has been discussed in depth. The document tries to highlight areas where research should begin immediately. Later, other aspects will be incorporated into a comprehensive attack on the problem.

The perception that there might be a serious CO_2 problem stems from the following:

- There has been a well-documented world-wide increase in atmospheric CO_2 concentrations since 1958; this growth has probably been occurring since the middle of the last century.

- The CO_2 increase in the atmosphere is equivalent to about 50% of the fossil fuel CO_2 released to the atmosphere.

- CO_2 transmits solar radiation but absorbs some of the outgoing long-wave radiation from the earth, the so-called "greenhouse" effect. Thus, qualitatively, CO_2 should act to warm the lower atmosphere and, by radiating more outgoing energy, cool the stratosphere.

- Different calculations of the greenhouse warming indicate that doubling of the CO_2 content of the air could result in a 1.5-3°C warming of the lower atmosphere. This global warming is sufficient to cause significant alteration of the present climate.

- While such climatic effects would be world-wide, they would likely not be uniform: some regions of the globe would experience greater changes from the present climate; others less.

- The doubling of atmospheric CO_2 could occur as early as 2030. There are sufficient fossil-fuel reserves to raise the atmospheric CO_2 many-fold if they are used.

- Natural rates of removal of CO_2 from the air are calculated to be so slow that it would take many centuries before atmospheric CO_2 levels returned to "normal" after additions ceased.

No responsible scientist will positively assert that climate changes will occur if we continue burning fossil-fuel or that the predicted climate changes would be catastrophic. On the other hand, no one can ignore the possibility that undesirable climate changes will occur. It is imperative that society be able to anticipate the consequences of future fossil fuel consumption.

To decide what actions society might wish to take, answers to the following questions should be obtained:

1. What will be the future atmospheric concentrations of CO_2?

2. What will be the climatic effect of these concentrations?

3. What will be the effect on the biological and physical environment of these climate changes coupled with the increases of CO_2?

4. What, if any, will be the effects on human societies of these changes?

5. In the event that these changes are undesirable, what actions can be taken to prevent them?

This document will lay out research plans to seek answers to these questions. It will emphasize the first two questions; further exploration of the last three will be needed. The method of formulating this plan is described in Appendix A. The plan draws heavily on the results of a Department of Energy-sponsored workshop held in Miami Beach in March 1977 and the National Academy of Sciences publication Energy and Climate issued in late 1977.

Each question will be discussed in turn but they are not necessarily independent. For instance, global climate changes, caused by CO_2 greenhouse warming, could alter the rate at which the oceans and biosphere absorb CO_2, thus affecting the rate of increase of atmospheric CO_2. Specific research programs are recommended to obtain answers to the first two questions, together with priority statements and estimated annual costs (in 1977 dollars). The priorities are based on the assumption that funding will grow from intially modest amounts to more substantial levels in a few years and represent the order in which the efforts should be started. It is not possible to give an accurate full-scale budget but we estimate, crudely, that between 15 and 20 million dollars will be needed annually to implement fully the recommendations embodied in this part of the overall plan.

Management Aspects

It was not intended that this document lay out specific suggestions of managing the suggested research, either on the national or international level. Nevertheless, these issues should be addressed as soon as possible.

A variety of programs now exist within a number of federal agencies. Some of these programs deal directly with the CO_2 question while others are conducted for a number of specific agency requirements but support the goals of this plan. These must be considered when any management decisions are made. In particular, a National Climate Program is being formulated and all U.S. climate efforts should be coordinated with it.

One of the goals in any U.S. program must be the involvement of the international scientific community, probably through one or more of the existing international scientific programs. The CO_2 problem is global in its impact. No single country's actions will be sufficient to control CO_2 releases. No single country can or should bear the entire research burden. International cooperation will be crucial if both scientific and policy problems are to be solved.

II. THE CARBON CYCLE: ESTIMATING FUTURE LEVELS OF ATMOSPHERIC CO_2

Predictions of future levels of CO_2 in the air will ultimately be made by improved numerical models of the carbon cycle influenced by man's activities. To model successfully the carbon cycle will require greater effort in the following areas:

1. Estimation of the sources of atmospheric CO_2, particularly anthropogenic sources.
2. Observations of atmospheric CO_2.
3. Study of the transfer of CO_2 from the air to other carbon reservoirs and the sensitivity of the transfer rates and reservoir sizes to climate changes.
4. Integrated modeling efforts.

A. Sources of Atmospheric CO_2

The main source of the observed increase in CO_2 is thought to be combustion of fossil fuels. Recently, however, the possibility has been raised that world-wide land-use practices, particularly deforestation, could also be contributing to the buildup. It is not thought likely that nautral sources, while important over the long history of the earth, are a significant factor in the recent rise.

It is important to determine if the fossil fuel releases are the only major net sources for the increase. If mankind feels drastic actions are necessary to control the level of atmospheric CO_2, curtailment of fossil fuel usage might not be the only required action.

The assumption is usually made that natural sources and sinks of atmospheric CO_2 were closely balanced before man intervened. Such sources of CO_2 as volcanic emissions, venting of methane along fault lines, and the oxidation of organic matter as permafrost retreats, are presumed to contribute only slightly to the observed atmospheric increase. A corollary to this assumption is that atmospheric CO_2 has remained roughly constant, at least in the few hundred years before the industrial revolution. Yet there is no real evidence that this is so. Not enough is known of the history of atmospheric CO_2 to confirm or deny the hypothesis of its relative constancy; in fact, no comprehensive theory exists to describe long-term cycles of CO_2. No specific research projects in this area are recommended now but some effort in the future might be found desirable.

1. Industrial sources

There are three aspects to the problem that should be considered: estimation of the carbon content of fossil fuel reserves in the ground; determination of the annual rate at which these reserves are converted to fuel and used (also other industrial sources such as cement production); and projection of future demand for these fuels.

The available reserves are well enough known today to argue that, if burned, atmospheric CO_2 will continue to increase to several times its present value. Nevertheless, better assessment on a country-by-country basis will be needed to keep track of the potential supply. The carbon content varies among these fuels and within each type. The carbon content and energy equivalent of each fuel source must be examined before its CO_2 potential can be accurately assessed.

The actual rate of consumption must be monitored (and converted to CO_2) to determine the current annual input. It is not always easy to estimate this globally because of the varying quality of the data base. Countries occasionally distort their fuel production and usage for internal reasons so cross-checks must be made. Detailed analysis of fuel use is also necessary to project future emissions.

The long-term estimation of future CO_2 inputs into the atmosphere is the most difficult estimate to make, depending as it does on a variety of socio-economic factors and political considerations. One can make various extrapolations based on historical consumption rates and population growths but these need constant checking and revision. Such factors as limitations on capital, environmental considerations, and availability of foreign exchange can inhibit a country's use of fuel. The energy contribution from fossil fuels will also depend on the availability and cost of alternative energy sources. Estimates of future fuel usage should be made on a country-by-country basis since the constraints to unlimited use will vary among the nations.

Priority and Funding

This effort should be started immediately and continue through the life of the program. An initial level of $50,000 would be useful, growing to $250-500,000 in a few years.

2. Terrestrial sources

A controversy exists as to whether the observed increase in atmospheric carbon dioxide is partly due to deforestation and other land-use practices, or whether the biota are absorbing a fraction of the fossil fuel CO_2. Current models of oceanic uptake of CO_2 suggest that, at most, only a small amount of excess CO_2 could be coming from the biosphere. Other investigators have claimed that net amounts equal to or greater than the fossil fuel contribution itself could be added to the air from deforestation. If the latter is currently the case, then the models of the various sinks for atmospheric CO_2 must be seriously in error.

Regardless of current and past biospheric trends, it is clear that future levels of atmospheric CO_2 could be substantially increased by large-scale forest clearing followed by oxidation of wood products and soil humus. There is little knowledge of the current rate at which land vegetation is being changed or eliminated with subsequent changes in stored carbon. These conversions can be deliberate, as with conversion of forest areas to agriculture, incidental to other activities or they may be natural as a result of local climatic shifts. It is desirable to estimate the current changes in the biosphere both to formulate and calibrate models of the carbon cycle as well as to determine the effects of future land-use changes on CO_2 levels.

In the section discussing the transfer of atmospheric CO_2 to other carbon reservoirs, substantial research on ocean uptake of CO_2 is proposed. If that work determines the oceanic sink to say, within a few percent and no other major non-biological sinks are found then, in principle, one would "know" the biosphere term as the difference between these known sources and sinks and atmospheric storage. Direct estimations of both oceanic and biospheric sources and sinks provide independent checks on each other.

2.1 The $^{13}C/^{12}C$ method

One method which might allow estimation of past biospheric changes involves the investigation of carbon isotope ratio changes in tree rings and possibly ice cores. Because both fossil fuel and biospheric CO_2 are deficient in the ^{13}C isotope when compared to atmospheric

CO_2, the release of CO_2 from both sources lowers the $^{13}C/^{12}C$ ratio in atmospheric CO_2. But fossil fuel CO_2 contains no ^{14}C; its emission reduces the $^{14}C/^{12}C$ ratio of atmospheric CO_2. Thus, the changes of both ^{13}C and ^{14}C content in atmospheric CO_2 potentially fix the magnitude of the net biosphere-atmosphere exchange. This tool could be especially powerful because globally integrated net biospheric fluxes can be derived.

Existing work on isotopic changes in tree rings (and ice) is very fragmentary and in some instances contradictory. Work by several institutions will be desirable to demonstrate that the techniques can truly give the magnitude of the biospheric input in the past few centuries.

2.1.1 The determination of precise ^{13}C isotope records

Aspects to be considered are:

a) The region from which the tree is collected. Isolated trees appear preferable to trees in a forest, where the growth of the trees may change the relative contribution of locally modified biospheric CO_2 or where forest cutting may have changed environmental conditions.

b) Selection of species with the least amount of internal variability. When taking samples of different parts of a tree, ring appreciable variability in ^{13}C content has been reported. The possibility of a change in isotopic composition with tree height also should be explored.

c) The influence on the ^{13}C record of the local temperature at the time of CO_2 uptake. The isotope fractionation is temperature dependent.

d) Separation of the chemical constituents of the wood. Cellulose appears to be the preferred component for isotope investigations. The reproducibility of the cellulose sample preparation is of critical importance. Variability in preparation leads to changes in the degree of cellulose degradation with a resulting change in ^{13}C isotopic composition.

e) The influence of growth factors, other than temperature, on the ^{13}C record. A variety of inter-related factors is responsible for the changes in ring widths of trees, and some of these factors could induce ^{13}C changes. Internal agreement of the ^{13}C record for trees of different age, and in the same area but with differences in environmental growth conditions, would reinforce the idea that the tree record accurately reflects atmospheric ^{13}C changes.

f) Analysis of at least a few dozen trees, of different species and from various parts of the globe, to provide global averages. Geographical differences in the record, if any, would have to be interpreted.

g) Variability in sample preparation. The ^{13}C changes to be detected are approximately one per mil or less. Thus variability attributable to sample preparation should be smaller than 0.05 per mil: present mass spectrometry should introduce variability no greater than 0.02 per mil.

2.1.2 The determination of the ^{14}C record

In addition to the ^{13}C record stored in the tree rings, the ^{14}C content should also be measured with a high precision. Tree rings contain the history of fossil fuel production through the dilution of the natural ^{14}C by fossil fuel burning (the Suess effect).

The Suess effect depends upon the partitioning of fossil fuel CO_2 between the atmosphere and oceans and thus provides a check on the model of the carbon cycle. The $^{14}C/^{12}C$ ratio yields the Suess effect between 1860 and 1950. After that date, the ratio is dominated by bomb ^{14}C. The Suess effect determination suffers from several shortcomings at present. First, there is variability in the $^{14}C/^{12}C$ ratio for the same date between trees in different regions. Second, there appear to be natural $^{14}C/^{12}C$ fluctuations even before 1860, apparently due to the modulation of cosmic rays by solar activity. A better understanding of the relationship between solar activity and ^{14}C production by cosmic rays would improve the reliability of the estimates of the magnitude of the Suess effect.

2.1.3 Determination of net biosphere fluxes

The evaluation of tree ring $^{13}C/^{12}C$ records as the basis for estimating the net amount of CO_2 due to deforestation or soil disturbance requires certain auxiliary information. First, one must assume a time history for the CO_2 release from the deforestation and soil disturbance. Second, and more important, an air-sea exchange must be assumed to make the calculation of this net biospheric source of CO_2. The ^{13}C method does possess the advantage of reflecting <u>global</u> contributions of excess CO_2 from both deforestation and soil humus. The reconstruction of the gross history of the carbon stored in the biosphere, mentioned in 2.2.1, can be compared with the results of this work to provide an independent check.

Priority and Funding

This isotope work should receive increased funding immediately: it is desirable that several groups work on the problem to resolve some of the discrepancies in the current estimates and to establish the validity of the techniques. If three separate groups were funded, approximately $500,000 annually would be needed with possibly an additional $150,000 at the start for instrument purchases; mainly, adequate mass spectrometers.

2.1.4 Atmospheric measurements of isotopes

It will also be desirable to begin immediate measurements of the isotopic ratios in the air to detect future changes in the carbon stored in the biota. This will be discussed further under atmospheric measurements.

2.2 Direct estimates of biospheric changes

Direct estimation of the changes in carbon stored in the terrestrial biosphere, mainly in the world's forests, requires determination of changes in both the carbon content of living matter and the carbon stored as dead organic matter. This will be a very difficult task and will require careful planning to determine if estimates can be obtained with the required accuracy in a cost effective manner.

2.2.1 Changes in living organic carbon pools

For the living parts of the biosphere, there is a good deal of undigested data already existing around the world. These data should be located, cataloged, and synthesized into histories of changes in the living plants of the world over the past few centuries.

Remote sensing may be the most feasible way of approaching the problem of monitoring future changes in reservoirs but this technique will have to be verified by substantial "ground-truth" measurements. A possible methodology is outlined below but the first step must be a study to determine its feasibility or that of any alternative. Thorough consideration must be given to a sampling strategy with proper statistical considerations. The undertaking will be costly and time-consuming and success is not assured at this time.

The methodology suggested is straight-forward. Imagery from the Landsat satellite (including Landsat C and D) should be used as the basis for the construction of a global vegetation map. Difficulties will be found where substantial changes in vegetation type occur over short distances, with defining soil characteristics and with choosing the appropriate resolution. High resolution radar and aerial photography will probably be required in some instances to identify vegetation types.

Such a map would provide new measures of the areal distribution of vegetation. It also would provide a basis for the identification of sample areas (quadrats) for further analysis using photography of higher resolution. These quadrats would be a basis for ground validation of vegetation and soil type to define the relationship between image characteristics and desired ground information. The quadrats should include samples of the major biomes with special emphasis on observing the effects of human activity.

A key feature of the task would be periodic resurveys of the sample quadrats. The time interval between surveys would be a function of rates of change of the vegetation (and thus could vary, with some sites studied more frequently than others), the precision required, and the manpower costs per survey. The selection of sample quadrats involves some difficulties, particularly if only a small number are selected. But it is speculated that repetitions at 2- and 5-year intervals of 200 to 1000 quadrats might detect a 2% change in areal extent.

Quadrat surveys reveal gross changes in vegetation. Changes in the carbon content per unit area, particularly in areas of no apparent change in vegetation type, are much more difficult to obtain.

It will not be possible to conduct extensive surveys of carbon content in every quadrat. Careful study and selection of representative sites within a limited number of quadrats may be necessary to extrapolate carbon content to a larger region. Whether a few intensive studies over a long period of time or simplified sampling at a larger number of sites is preferable will have to be determined as part of the feasibility study.

The quadrat surveys will need to be highly disciplined and closely coordinated with the effort to synthesize all the data into estimates of carbon pool changes. The synthesis effort will require experts in statistical modeling as well as land-use analysis.

Priority and Funding

The feasibility study should begin immediately; $75,000 should cover a one-year effort. If this study indicates further work is desirable, a rough estimate of cost, including on-ground sampling, is 3 million annually.

Work should start immediately on constructing the historical vegetation maps. The cost is estimated at about $60,000 per year for 5 years.

Upgrading of present estimates of biomass should also start as soon as possible. This should cost about $40,000 per year for 3 years.

2.2.2 Changes in soil carbon pool sizes

The size of the carbon reservoir represented by dead organic matter, including surface litter and soil carbon, is less well known than for living matter. This pool may contain over 3 times the amount of carbon in the standing vegetation. Further it is not clear how much of this carbon readily exchanges with the atmosphere or how much could be released to the air when man disturbs the soil or the vegetation. Such releases could be particularly important in large-scale deforestation and in the draining of wetlands.

It cannot be assumed that loss of carbon from the soil immediately contributes to increases in atmospheric CO_2. Some of the lost carbon could be transported via rivers to the oceans without entering the atmosphere at all.

The problem of estimating changes in soil carbon on a world-wide basis is extremely difficult. It may not be possible to estimate, with sufficient accuracy, their net contributions to atmospheric CO_2 in the past. It will be important to understand the effects of future alterations of land-use practices on soil carbon and whether these practices could lead to substantial changes in atmospheric CO_2. It is also possible that much of the soil carbon exists as relatively refractory carbon compounds unlikely to be disturbed by man's activities or able to enter the atmosphere. If so, the importance of soil alterations could be overemphasized.

As a first step a more accurate estimate of the global soil organic carbon content and its form (whether refractory or easily altered) is needed.

Experiments should be designed to determine the forms and amount of carbon released from soil organic matter under specified environmental conditions.

The use of carbon isotope ratios should be explored as diagnostic tools to determine the age and transformations of soil organic matter. The ages of soil organic matter range from a few years to many thousands, depending on the kind of soil. Within a given soil, the organic matter may be of distinctly different ages. The age of the soil organic matter has a definite bearing on its stability and hence its rates of decomposition and transformation.

A study is needed to assess age and turnover time of the organic fractions which contribute to the carbon content of soils. The goal of this research would be estimation of the extent to which man's activities may have affected releases of carbon from soil organic matter of various ecosystems. Transfers of carbon between soil layers and into solution should also be considered.

Some special attention should be paid to peat regions, bogs and other wetlands. Although not great in total area, the primary productivity of some of these regions is large, and they are under intense human pressure in many parts of the world. Peat is used for fuel and many wetlands are being drained to provide dry land for various purposes. This practice can release carbon to the air as well as reduce the annual carbon fixation of these regions.

Priority and Funding

As with estimates of the living organic matter initial work on upgrading estimates of soil carbon should begin now. A 3-year study costing $100,000 annually is estimated.

A feasibility study to determine if one can design appropriate experiments and procedures to anticipate contributions to atmospheric CO_2 from soil disturbances should be started immediately. A cost of $75,000 is estimated. This should be done in concert with the feasibility study for assessing changes in the living carbon pool. If subsequent work appears practicable, an annual cost of $300,000 is indicated.

2.3 Changes in inorganic terrestrial carbon

Knowledge of soil and water carbonates needs to be improved. Of the minerals exposed on the land surface, 9% are calcite and dolomite, and from this one estimates over 1600 x 10^9 tons of carbon are contained in the first meter of soil. Like soil organic matter, a large fraction of this pool may be relatively passive. But changes do occur under irrigation or with changes in climate and vegetation. Calcareous soils in humid regions have less carbonate but faster turnover. A preliminary study of the magnitude of this pool and its chemical dynamics, including its role in establishing isotope ratios, would define problems needing research. In addition to the normal variation with weather and climate, we need to know more about deep leaching of bicarbonate, recycling of fossil ground water saturated with carbonates, the influences of acid precipitation, agricultural liming (fossil carbons) of acid soil, and about the significance of apparent imbalances in global cycling of calcium.

Priority and Funding

Preliminary survey and estimation of the size of this pool should start as soon as possible. A 3-year program at $50,000 per year should determine how much further work is needed: if further work is needed, $200,000 annually ought be required.

2.4 Synthesis and prediction

Additional effort in synthesis is needed to integrate the findings of these studies of terrestrial carbon cycles into predictions for global carbon cycling. Prediction can be done effectively only with simulation models requiring research in the highest priority.

Past and present data developed in other parts of the program should be integrated into the best possible models of carbon pools and flux rates through the terrestrial system. The model(s) should focus on primary production, prediction of detritus flow and biomass changes. A special model is needed for the prediction of vegetation change while a simpler model simulating the behavior of even-aged monocultures would handle the main issues in the dynamics of carbon storage. Some additional background is needed to predict soil-vegetation behavior variations with climate and CO_2 change. Most of the experimental studies required for such predictions already exist although additional information will be needed on the influence of elevated CO_2 in controlling plant development (see Section II, C.2.), on the integrated behavior of trees to increased photosynthate supply, and on soil behavior including carbonate solubility.

It should also be noted that resolution of the carbon cycle may well require simultaneous resolution of the cycles of nutrients, particularly nitrogen, phosphorous and sulfur.

Experience has shown that modeling and synthesis suffer in conception and execution if divorced from data acquisition and experimental studies. The need to insure that modeling is a close adjunct of measurement and not an isolated theoretical exercise cannot be overemphasized.

Priority and Funding

This synthesis effort should begin as soon as the data become available in a useful form. $50,000 annually should be budgeted for the work.

B. Atmospheric Storage of CO_2

1. Monitoring network

The present CO_2 baseline monitoring stations are located at 11 remote sites to determine the global background concentrations.

International cooperation among the participating nations is being organized through the World Meteorological Organization of the United Nations. The network should be expanded by about 10-15 more stations at equally remote locations. Such an expanded network will provide truly global CO_2 growth rates and horizontal gradients of CO_2 which may suggest the places and times of sources and sinks of atmospheric CO_2. The seasonal CO_2 variations at these stations might yield clues to changes in regional photosynthesis, and the interannual changes might indicate changes in the global atmospheric circulation or sea surface temperatures. Occasional aircraft flights to give both horizontal and vertical distributions are a useful adjunct to single-point stations. The present and planned network use non-dispersive infrared analyzers (NDIR) for continuous measurements. There has also been considerable success in measuring CO_2 by obtaining flask samples of air for analysis at a central laboratory with the same apparatus. At some locations, the flask method could be a relatively inexpensive substitute for continuous measurements.

The non-dispersive infra-red analyzers require standard gases. It is important that all results, whether flask or continuous techniques, be traceable to the same standards.

In many cases the new stations would not be on U.S. soil and so require international cooperation. Other countries, through the World Meteorological Organization, are also contemplating expanded monitoring.

U.S. planning of new stations should proceed insofar as possible in coordination with the plans of these countries.

For reasons discussed in other sections, the monitoring of atmospheric CO_2 should include the determination of the isotopic composition of atmospheric carbon: $^{13}C/^{12}C$ and possibly $^{14}C/^{12}C$ should augment the CO_2 concentration measurements.

Some consideration should be given to archiving samples of air for future analysis under the supposition that future technology may permit a more refined analysis. Before storing samples, however, it should be determined that storage techniques would preserve the sample's integrity.

Priority and Funding

Expansion of the networks should begin as soon as possible. Flask sample stations (10-15) could be started for about $100,000 and ^{13}C and ^{14}C measurements and analysis could be added to the existing stations for another $100,000 per annum. Additional continuous monitoring stations would cost about $70,000 per annum each.

2. Standard gases

The need for continuing, long-term measurement of atmospheric CO_2 has already been demonstrated. The availability of CO_2 standard gases calibrated to an absolute standard is essential.

Current CO_2-in-nitrogen standards at the Scripps Institution of Oceanography, the WMO International Calibration Center, are based on manometric (pressure) methods. Scripps can also prepare similar CO_2-in-air standards. The NOAA GMCC Laboratory has developed á dilution technique capable, in principle, of the desired accuracy. Finally, the National Bureau of Standards (NBS) is developing gravimetric methods which may ultimately become the world standard CO_2-in-air gases. From the absolute standards, one calibrates working gases used in the actual CO_2 concentration determinations. An orderly integration of any new standards must be accomplished by intensive intercomparison between new CO_2-in-air standards and existing CO_2-in-N_2 Scripps standards.

A period of several years will be required for determining the long-term stability of any new primary and working standards gas. During this period, it is vital that the current gas standards and measurement equipment be maintained. Because the CO_2-in-N_2 standards present problems for the NDIR, future CO_2 standard gases are likely to be CO_2-in-air.

Priority and Fudning

Under no circumstances should any interruption in the present program be allowed. Development and maintenance of standard gases to improve capability should cost about $100,000.

3. Measurement instruments

Almost all background measurements of CO_2 in the gas phase have been made with a technique employing the NDIR CO_2 analyzer. While this method is adequate, it has several disadvantages which might possibly be avoided by new, but untried instruments. Two shortcomings of the NDIR analyzer are: the need to dry relatively large air samples and the need for frequent intercomparison with CO_2 gas standards.

Gas chromatography may be developed to provide precision as good as that for NDIR analyzers but with much reduced demands for working gases. Laser absorption spectroscopy also is a promising measurement technique for the isotopic composition of carbon and oxygen in CO_2. Another possibility is to use coincidences of emission lines of a CO_2 laser with absorption lines of CO_2.

Priority and Funding

New instrumentation is important and opportunity should be taken to capitalize on the newer technologies. $100,000 should be budgeted annually for this activity.

C. Sinks for Atmospheric CO_2

1. Oceanic sinks

The ocean is ultimately the major sink for fossil fuel CO_2. To predict reliably future atmospheric CO_2 levels, one must thoroughly understand the dynamics of this CO_2 uptake and the transfer of CO_2 from the surface waters to deeper waters. Five important aspects are involved:

1) The exchange rate of CO_2 between air and sea must be known as a function of temperature, sea state, and possibly wind speed and water chemistry, including the effects of surface films.

2) The thermodynamic distribution coefficient of CO_2 gas between air and sea water (the CO_2 buffer factor) must be known as a function of temperature, salinity, alkalinity and total dissolved inorganic carbon concentration.

3) The patterns and rates of vertical and horizontal transfer within the sea must be determined, not only to estimate current conditions but to anticipate the impact of climate changes on these rates.

4) The vertical flux of particles transporting carbon downward through the sea should be assessed. The possible influence of environmental changes induced by man's activities on these fluxes must be determined.

5) The role of $CaCO_3$ in determining the uptake of CO_2 from the air should be examined. The dissolution of $CaCO_3$ in marine sediments enhances the capability of the ocean to absorb fossil fuel CO_2 from the air. For the shallow sediments, the critical mineral is high-magnesium calcite; for the deep sea sediments, the critical mineral is calcite.

1.1 Gas exchange rate

Two alternative techniques for estimating the exchange rate of CO_2 between the ocean and air offer promise. One involves the measurement of the vertical flux of CO_2 in the air immediately above the sea, either by eddy correlation techniques or by inferring the flux from observed gradients of CO_2 concentrations in the air. The former is preferred if the instrumental difficulties can be overcome. Recently, the eddy correlation method has been used at sea by investigators at the Bedford Institute of Oceanography in Canada. Some modifications of a method for sampling separately upward and downward moving air also merit investigation.

A second method involves measurement of ^{222}Rn which is formed in the sea from the decay of ^{226}Ra. Less radon is observed in the water than expected from the decay rate of radium implying an escape of radon to the air. From careful observations, a gas exchange rate can be calculated. Results of the ^{222}Rn method are at variance with estimates derived from ^{14}C studies and reconciliation of these estimates should be pursued to produce a better understanding of the air-sea exchange process.

Application of these methods to all oceans would be prohibitively expensive. Rather, intensive investigation at one or more locations could reveal how the exchange rate varies with sea-surface temperature, sea state and other ambient conditions enabling extrapolations to the whole ocean.

In addition, determining the rates of penetration of bomb and natural ^{14}C into the ocean can continue to give information on air-sea transfer. A possibility exists for estimating past transfer by examining the ^{14}C content of shells and corals recently deposited.

Priority and Funding

This work does not require immediate funding; one-to-two years delay would not be crucial. The estimated cost is $200,000 annually for about 5 years.

1.2 The CO_2 buffer factor

The buffer factor represents the ratio of the fractional change in pCO_2 in the air to the fractional change of pCO_2 in the water at equilibrium. It determines the net increase in oceanic CO_2 for a given change in atmospheric CO_2. Its mean value is currently estimated to be between 7 and 11, but it is necessary to know its value more precisely in the present and future oceans. To do this, more precise measurements are required of the alkalinity, total CO_2, salinity, temperature, borate content and solubility of CO_2 gas as well as the first and second dissociation constants for carbonic acid and the first dissociation constant for borate in the sea water of interest. These properties can be measured in the laboratory from carefully obtained samples of sea water. A pilot study is underway at Scripps Institution of Oceanography to determine the feasibility of these buffer factor measurements. If they are feasible, then sampling of the world's oceans to determine the buffer factor values could be carried out in conjunction with other ocean surveys proposed in this plan. Furthermore, accurate determinations of these properties would help reveal CO_2 trends in the ocean.

Priority and Funding

This work should begin as soon as possible. Estimated cost is $300,000 annually for 10 years.

1.3 Transfer within the ocean

For at least the next several hundred years, transfer of CO_2 from the surface waters to deeper waters will constitute the rate-limiting step for oceanic uptake of CO_2. This transfer takes place by turbulent mixing into the main thermocline, by organized circulations where water previously in contact with the air sinks, mainly at high latitudes, and by the sinking of carbon-containing particles of biological origin. Much of our knowledge of the penetrations of CO_2 into the oceans stems from observations of man-made tracers, notably tritium and ^{14}C produced in nuclear weapons tests. Continued surveys of these and other transient tracers are likely to be our main tool to provide an understanding of oceanic circulation and mixing.

To obtain data to provide the basis for modeling efforts, a time series of oceanographic surveys is proposed, with the specific aim of measuring the distribution of man-made transient tracers—tritium, its decay product ^3He, ^{14}C, and fluorocarbons—in the ocean. The surveys should consist of repeated cruises in the world oceans with special emphasis on the North Atlantic, the Antarctic Circumpolar Current area, the northernmost Pacific, and the Arctic Ocean. The first two of these areas are regions where CO_2 is dissolved and sinks with the newly formed water masses. The experience from the GEOSECS program indicates the preferred sampling areas and frequencies. There should be several north-south tracks in the Atlantic and in the Pacific, and more extensive surveys in the subarctic seas and a special program in the Arctic Ocean. Each such survey cycle would require approximately five years of ship time and the first should begin to be planned immediately and started in 1980. Sampling of the transient tracers should be accompanied by measurements of hydrography and nutrients. Laboratory facilities should be planned to handle the analytical load at a steady production rate during the duration of the entire program.

Well-established techniques are available for the measurement of tritium, ^3He, and radiocarbon in oceanic samples. The quantity of water needed for tritium, helium and probably the freons, is only about 1 liter or less but ^{14}C now requires about 200 liters of seawater, preferably with extraction on board the ship, although some techniques show promise of reducing this requirement. Laboratory facilities for radiocarbon and tritium measurements are available in this country, although some expansion must be undertaken in order to handle the anticipated quantity of samples. In the case of freons, the development is presently hampered by uncertainties in the gas standards. The potential is available, however, for making freon measurements on board the ship collecting the samples.

Consideration should also be given to the deliberate injection of a known quantity of a tracer to measure transport and diffusion in important areas of the oceans. Such a program would have to consider possible environmental side-effects of the tracer leading to ramifications in the international political arena as well. Thus, while questions about safety of the environment and political implications will have to be answered, the knowledge obtained from such a program is potentially very great.

Priority and Funding

Because the suggested programs for monitoring the transient tracers and other oceanographic work are costly and long-term, very careful planning is needed. The first step should be a contract to an organization familiar with the operation of oceanographic programs to formulate a long-term plan. The effort may include a workshop of experts. Consideration must be given to logistics, ship availability, and costs as well as the subsequent chemical and radiochemical analyses. This planning should begin immediately with $50,000 devoted to it. A full-scale program could cost about $5,000,000 annually including ship time. A ship dedicated to the program, preferably one uncontaminated with ^{14}C, would be most desirable.

1.4 Organic carbon in the ocean

Carbon-containing particles fall from the surface water to deeper waters as fecal pellets and dead organisms. Most of these particles subsequently decompose in the deeper water, although some amount may be refractory and transfer a small amount of carbon into the sediments. The decomposed carbon goes into the larger pool of dissolved organic carbon (DOC). Some particulate organic carbon (POC) and the DOC is oxidized back to CO_2 in the water column or sediments, probably by bacteria.

There is much to be learned about this cycle of organic carbon in the oceans. A first step would be to determine the flux of POC from the upper waters using sediment traps. The difficulties with current sediment traps should be resolved first, however.

Changes in biological productivity of the surface waters could occur because of increased CO_2 possibly coupled with increased nutrient input from the land. It is possible these changes could alter the carbon flux in the ocean. Also, changes in the oceanic carbon flux may be brought about by physical processes such as climate modification.

A second issue is the nutrient and organic carbon transport from the land to the sea, mainly by rivers but also through the air. If significant man-made fertilization of coastal waters is taking place, and some of the enhanced organic matter transferred to the sediments, another mechanism of transferring and storing carbon in the ocean is taking place that man is influencing. Some nutrient transport from land to sea is undoubtedly occurring but the quantities involved may be insignificant on a global basis. This question should be investigated on a moderate scale to determine the order-of-magnitude of river to ocean transfer.

Priority and Funding

River transfer studies as well as measurements of the vertical transfer of particulate carbon in the ocean should be planned. The first step to be taken should be two workshops on the subjects of particulate carbon transfer in the rivers and the oceans, each at a cost of about $30,000: full scale program costs could be 1-2 million dollars annually.

1.5 Sediment dissolution

a) Shallow water sediments

Most current models of oceanic uptake of CO_2 from the air are based solely on increases in dissolved CO_2 species and ignore reactions with the solids in the sediments. The fossil-fuel-produced CO_2 has not yet reached the deep ocean sediments but it is possible that some shallow water sediments, notably the high-magnesium calcites could already be dissolving. If this is indeed happening, then the reaction of the carbonate ions with the CO_2 to make HCO_3^- ions could be enhancing oceanic CO_2 uptake from the atmosphere: this could be an additional sink for atmospheric CO_2.

To determine if an extensive research program dealing with carbonate dissolution in shallow waters is needed, laboratory and aquarium studies coupled with a small in-situ study in a near-shore system ought first be undertaken. These studies would determine if, indeed, the high-magnesium calcites are capable of dissolving under current conditions. If these pilot studies suggest expanded effort, then the extent of high-magnesium calcite in the sediments should be determined. It will be important to assemble the available information on the areal distribution of the mineralogy of shallow-water sediments. Where the available information is inadequate, further surveys would be needed. The nature of these surveys and the kind of information generated is much the same as will be needed for the deeper carbonate sediments to be discussed below.

b) Deep water sediments

Calcite is the critical deep-sea sediment for the ultimate absorption of CO_2 by the ocean on the extended time scales of more than a few hundred years. The bulk of the available calcite lies below depths of 2.5 km, but above the abyssal planes and roughly half of the world's total calcite lies at depths between 3 and 5 km in the Atlantic Ocean.

It is necessary to have more detailed maps of the calcite of marine sediments than now exist. An areal distribution of the calcite content of the upper few tens of centimeters of sediment should be obtained by depth intervals in each ocean basin. The cores for this mapping are largely in hand. The topography of the sea floor is also sufficiently well known. The tasks to be done are:

- establish the areal extent of calcite sediments;
- $CaCO_3$ analyses of existing core material;

- synthesis of all these data into a format suitable for mating with models of deep sea circulation and mixing.

Beyond a knowledge of the distribution of calcite, more knowledge is needed about the kinetics of its dissolution. How does the rate of dissolution change with a decrease in the $CO_3^=$ content of the bottom water? How will this change depend on the percentage of calcite in the sediment? The answers will require a knowledge of processes at the sediment-water interface and within the sediment pores.

The kinds of research needed for this aspect of the program are as follows:

1) Measurement of the absolute rate of $CaCO_3$ accumulation as a function of water depth on the flanks of oceanic ridges in various parts of the ocean.

2) Techniques to determine, from the state of preservation of certain foram and coccolinth species in a given sediment, the amount of dissolution they have experienced.

3) Laboratory studies of the controls of the rate of dissolution of actual sediments.

4) Means of quantifying rates of biological mixing of the sediments. Deliberate deposition of tracer material on the sea floor offers promise.

5) Determination of the thermodynamic solubility of calcite, aragonite and other carbonates in the temperature range from from freezing to at least 35°C and in the pressure range 0-700 atmospheres.

6) Studies designed to characterize the fluid dynamic benthic boundary layer. Numerous reports tell of scum coatings on benthic sediment. Fluid dynamic theory allows that stagnant films several millimeters in thickness may exist. If so, this film (or fluff) could provide a major barrier to $CaCO_3$ dissolution.

Priority and Funding

a. Simple experiments should help decide whether work on shallow-water dissolution needs full-scale support; about $25,000 should be sufficient for initial experiments. If they indicate more work should be done, it should be started next year. An initial investment of $200,000 would be needed. If a full-scale program is desirable, $1,000,000 annually would be needed in addition to ship support which might be available elsewhere. This effort could be combined with others, however, reducing the cost substantially. A full-scale program should need only about 5 years to complete.

b. Dissolution of deep water sediments is important in the long-run but there is no need for immediate funding. Several years could elapse without impairing the program. Costs could run as high as $1,000,000 annually.

2. Response of biota to increased atmospheric CO_2

Some models of the carbon cycle assume that the excess CO_2 enhances photosynthesis. While some commercial crops have shown increased yields when grown in greenhouses at elevated CO_2 concentrations, it is not certain that net carbon in the plant material has been increased. Furthermore, it is not yet clear that similar results would occur under natural conditions where water and nutrients might be limiting growth.

The determination of the excess CO_2 which can be absorbed in the biosphere is the main issue addresses here. In addition, increased CO_2 could alter ecosystem compositions if different species of plants respond differently to increased CO_2 in the natural environment. If some particular species should acquire a competitive advantage it does not now enjoy, the composition of some ecosystems could change with consequences for herbivores and higher trophic level animals. It is worth noting that these hypothetical results of CO_2 fertilization could take place even if the climate does not change. Much of the research program recommended here will bear on these problems as well as the question of increased carbon accumulation in the biosphere.

To acquire information on the plants' responses to higher CO_2 levels, it will be necessary to consider the effects of increased CO_2 on photosynthesis, nitrogen fixation, water-use efficiency of plants and, of course, actual growth. Photosynthesis is the central process governing the primary productivity of all green plants. The availability of nitrogenous nutrients is considered a major limiting factor to plant productivity and it is not clear to what extent enhancement of photosynthesis by increased CO_2 will increase N_2 fixation. Water use by plants is controlled largely by the stomata which in turn may be influenced by the ambient CO_2 concentration. It is possible that increased atmospheric CO_2 could result in increased water-use efficiency by allowing the photosynthesis rate to remain unchanged while reducing the demand for water. On the other hand, plants may simply increase photosynthesis for the same water usage at elevated CO_2 concentrations. Note that increased primary productivity by itself is not sufficient to slow down the atmospheric CO_2 growth. Only if this increased productivity results in a continuous increase in stored biomass or detritus will it increase the strength of the sink of excess CO_2.

A research program should include:

1) Quantitative determination of the responses of stomatal and non-stomatal components of photosynthesis to CO_2 enrichment under a range of combinations of light and temperature regimes. Experimental plants must include ecologically diverse representatives from the world's major biomes and they must be grown at present and elevated CO_2 concentrations (probably up to 5 times present).

2) The determination of the influence of nutrient status, especially nitrogen and phosphorus, on the response of stomatal and non-stomatal components of photosynthesis to CO_2 enrichment.

3) The determination of the influence of warmer than optimal temperatures and water stress on the response to CO_2 enrichment of stomatal and non-stomatal components of photosynthesis.

4) The determination of the effect of CO_2 enrichment on N_2 fixation in several different major kinds of symbiotic and non-symbiotic plant-microorganism associations.

The research proposed in 1) through 4) should be carried out mainly in the laboratory on plants grown under controlled conditions.

5) Studies of the effect of chronically increased CO_2 on growth are also needed. This includes rate and water use efficiency of biomass production, carbon allocation to the various plant organs, morphogenesis, phenology and reproduction. It is highly probable that important differences exist in the mode of response among different species, particularly between different life forms (e.g., annual plants and trees) and species of contrasting ecological origins. Any effects of increased CO_2 on morphogenesis and phenology, especially floral induction and other reproductive events, can be expected to be strongly dependent on the seasonal variation of several environmental factors, in particular day length and light quality. The possibility of conducting a major part of this research at natural field sites, located in different biomes

and latitudes should be contemplated. Controlled growth experiments in simulated natural environments, possibly using naturally illuminated greenhouses, should be studied for feasibility.

6) Finally, conceptual and mathematical models relating the various responses of photosynthesis and growth to increased CO_2 will be needed. These models should be continually developed and updated as the data base increases. The final goal is the construction of reliable predictive models of the overall effect on global productivity and storage of excess CO_2.

Priority and Funding

This work should be planned immediately. It will require several separate groups to carry out all that is recommended: initially some of these scientists involved in growth chamber work should be brought together in a planning workshop. Initial work should be done on tropical forest species if the total program cannot be support now. Costs could be about $1,000,000 annually for a full scale program at several sites with an additional $1,000,000 possibly needed to build the appropriate facilities.

D. Models of the Carbon Cycle

All the above programs involve model development as part of their efforts but an additional component devoted to integrating the results of these studies into a global carbon cycle model is needed. Its goal, of course, will be to predict the future atmospheric CO_2 concentrations from scenarios of fossil fuel use and land-use changes. To be valid, these models must be able to reproduce not only the currently available data on atmospheric CO_2 growth, but be compatible with the distribution of the isotopes of carbon in the atmosphere, oceans and biosphere.

Progress in this area will depend upon progress in determining the components of the carbon cycle and their reactions to increased atmospheric CO_2 coupled with any attendant climate changes. Attempts to model the carbon cycle will also likely disclose areas needing particular research emphasis in the other components. This effort must proceed, as with all modeling efforts, in close association with data gathering and analysis.

There is some modeling of the carbon cycle now going on both in the U.S. and abroad. Cooperation among the groups is essential. There is marked similarity in their assumptions and parameters but this may indicate the paucity of information upon which all are based.

Specifically recommended are more groups, with differing disciplinary emphasis, to synthesize the data into predictive models as they become available. As noted below, this need not be done immediately. A useful first step will be the convening of an international workshop of those now doing carbon cycle modeling. From this will come suggestions for specific further steps.

Priority and Funding

The workshop should be conducted as soon as possible: \$30,000 would be sufficient to support it.

Within a few years, additional groups should be established to devote their energies to the task, on a continuing basis. Annual costs should be about \$200,000 since the groups are assumed to have the necessary computer facilities available to them.

III. CLIMATE EFFECTS OF INCREASED CO_2

The climate system includes not only the atmosphere but the oceans and the land surface, including the ice and snow covered regions, and the biota. The uneven distribution of these features around the globe coupled with differences in land elevation, interact in ways not now fully comprehended with atmospheric driving forces to comprise the climate system. The obvious forcing functions are astronomical in origin ranging from the daily cycle of the earth's rotation to the seasonal cycles caused by the motion around the earth's orbit. Variations in this orbit may affect climate on scales of tens of thousands of years. Variations in the sun's energy output, if any, would also affect the climate. Furthermore, large volcanic eruptions, by putting massive amounts of material into the stratosphere, affect the climate. There may well be other, undiscovered, forces at work.

The climate system maintains the earth's energy balance by transporting heat between equatorial and polar latitudes. If the temperature gradient between tropics and poles should change, as current models suggest would happen if atmospheric CO_2 increases substantially, then the energy exchange effected by the climate system would also change and some new circulation patterns could evolve. These new circulation patterns could well lead to substantially new regional climates. Precipitation as well as temperature might be modified and these regional changes could be greater than changes in the global average.

Observations show that climate is variable without man's intervention. The causes of this natural variability are little understood although they have affected man's activities significantly throughout history. At present there are plans being formulated for intensified research programs, both nationally and internationally, to improve the understanding of the whole climate system and its variations. There are several studies of climate research requirements (see suggested readings) and these suggested programs will not be reproduced here. Long-term study of the CO_2-climate problem must be integrated into these emerging international programs. Resolution of the CO_2 problem will depend on advances in climate research which have broader applications. If one is to have confidence in predictions of the perturbations of climate caused by CO_2, the unperturbed state must be understood much better. The program suggested below stresses those increments of a total climate research program that are directed toward the CO_2 problem.

A. Radiation

The radiative properties of carbon dioxide are reasonably well known. There remain, however, some possible problems with the radiative properties of a mixture of gases with overlapping absorption bands. Water vapor is the prime example of such overlapping lines of absorption. Other gases, particularly man-introduced gases such as the fluorocarbons, also absorb strongly in the infrared and contribute to "greenhouse" warming. A second aspect is the possible saturation of CO_2 lines and bands when the CO_2 reaches high enough concentrations. No specific recommendations of these questions are suggested now but the possibility that some effort should be devoted to studies of radiative properties of gas mixtures should be kept in mind.

B. Computer Simulation of CO_2-induced Climate Changes

The consequences of increased atmospheric CO_2 to the climate are estimated from computer simulations. These simulations, which indicate that a doubled CO_2 concentration would increase the global mean temperature of the lower atmosphere between 1.5 and $3^{o}C$, are crude even though they employ the most sophisticated techniques and machines available. Several factors not now included in simulation models are thought to be important and others not now known could also prove to be significant. In addition, none of the climate models applied to the CO_2 problem has contained a realistic topography or distribution of land and water although the means for doing so are available. Thus, regional climatic changes cannot now be predicted and regional modifications of precipitation may be the most crucial consequence of CO_2 increases in the atmosphere.

The major improvements needed in all models for climate studies are generally recognized to be:

1) incorporation of an interactive and coupled ocean;

2) improved treatment of clouds and their influence on the radiation budget; and

3) improved treatment of the cryosphere, notably snow and the floating ice packs.

While it may well be decades before a sophisticated ocean model can be developed and coupled to an atmospheric model, it is possible that simpler models will yield useful climate predictions. For example, a simple ocean-atmosphere model whose mixed-layer temperature is brought into thermal equilibrium with a warmer atmosphere would be such a useful early candidate. Advantage could be taken of the fact that the response time for adjustment of the entire ocean to an atmospheric change could take many centuries and so all the details of the deep ocean circulation may not need to be included.

If global cloudiness should change (both amount and heights) in response to the warming and circulation changes, an important feedback mechanism could exist which is now handled only crudely. Although some work suggests that cloudiness feedback may not be so important as previously thought, more satisfactory treatment of clouds is needed than is now in the models.

Of the five regimes of ice and snow (permafrost, glacier, ice sheets, sea ice and seasonal snow) most attention should be paid to improving the treatments of sea ice and the seasonal snow cover for inclusion in atmosphere-cryosphere climate models. Drastic changes in ice and snow extent would change the earth's albedo: reduction of the extent of sea ice would increase the moisture supply to polar air.

Much of the above concerns improvements in General Circulation Models (GCM) which are 3-dimensional, global, or at least hemispheric, models. It is from these sophisticated simulations that the best hopes for predicting regional climate changes will derive. There is room, however, for work on less elaborate and hence less expensive and time consuming one- and two-dimensional models. Some of the latter can be used for investigations of specific physical processes and for studies of the sensitivity of climate systems to variation of certain variables and should be used in concert with the GCMs. These models can also be used to determine effects of other radiatively active gases and particles which man releases to the air and which may obscure or enhance the CO_2-induced climate change.

It is important that several groups conduct the modeling efforts. Much of the necessary work is already being carried out now or planned by a number of groups with the necessary competence and computer facilities. Such parallel work by the different groups is to be encouraged since each model has different characteristics and approaches. Coincidence of results among the groups will lend additional credence to the forecasts. Divergence of results will immediately suggest areas where understanding is lacking.

Finally, it should be noted that current understanding of today's natural climate system is inadequate. It is not even known whether climate is a deterministic response to a variety of natural forcing functions of many time and space scales; that is, whether a unique set of boundary conditions and forcing produces a unique climate. Any fundamental insights into the dynamics of the natural climate system will be of great value in determining the response of the climate to increased carbon dioxide.

Priority and Funding

Much of the modeling work is now being supported and there is doubt that entirely new groups can be formed, trained and become productive in the near future. Nevertheless, some existing groups could devote themselves more intensively to CO_2-related problems if funding were available. Highest priority would be given to the development of coupled ocean atmosphere models. Second priority would be given to better handling of cloud properties in the models and then to coupled cryosphere-atmosphere simulation: each is important and will have to be incorporated into a final model. About $250,000 to $500,000 could be added to current annual funding levels, growing to $1,000,000 or more in later years.

C. Reconstruction of Past Climates

Knowledge of the climatic history of the earth is important both to anticipate what could happen and to provide data to help validate the computer simulations. Initial emphasis should be put on periods when the earth was warmer than it is now—such as the altithermal—but better understanding of all past climate will help to elucidate the underlying dynamics which will have to be known to give any model credibility. These reconstructions should include, as far as possible, the past ocean and biosphere and the atmospheric CO_2. The history of the various climate forcing functions is needed as well as their manifestations in temperature and precipitation.

Priority and Funding

Current efforts on this topic should receive additional support within a year or so. An initial annual expenditure of $100,000 is estimated, increasing in later years.

D. Observations and Analysis of Current Trends

Current estimates suggest the earth has experienced only a few tenths of a degree warming due to the increased CO_2 since the Industrial Revolution. This is small enough that it would be masked by the known natural variations in climate. It has been stated that an unambiguous CO_2 signal might be evident by the year 2000 if emission trends continue and the computer forecasts are near the correct answer.

No specific additional research on this topic is recommended now but the current observational networks must not be degraded. Certain areas such as the polar regions and the stratosphere should be watched carefully since they are the areas where the CO_2 signal might first be seen. Monitoring of these areas could provide early indications of the anticipated changes or if absent, they might reassure us that the changes have been overestimated.

No specific funding is recommended at this time, however.

IV. EFFECTS OF CLIMATE CHANGE AND CO_2 INCREASES

It is necessary to translate any anticipated climate changes into effects on the biosphere as well as on the cryosphere and ocean circulation. Since some of these effects might well feed back to the climate system itself and the carbon cycle, some have been targeted for research in the preceding sections. Other specific studies should be pursued to define better, and so anticipate, the consequences.

The following areas should be examined:

- Marine organisms could be affected by increases in dissolved CO_2. The slow lowering of oceanic pH and lowering of the super-saturation with respect to $CaCO_3$ of surface waters could affect the ability or organisms to form carbonate shells and skeletons. Lower pH could also lead to an increase in metal-ion concentrations by reducing the sequestering of metals.

- Changes in atmospheric circulation could produce changes in oceanic circulation. Marine productivity might be reduced if the rate of upwelling were decreased since the latter controls the fertilization of certain surface waters.

- Attention must be paid to effects of increasing CO_2 on acquatic life in fresh waters. Some fresh waters, unlike the oceans, are poorly buffered and pH changes could be larger than in the ocean. The consequences of these changes together with changes in the carbon compounds may be serious for acquatic life even in the absence of significant climate changes.

- Greatly elevated CO_2 concentrations in the air may have effects on non-photosynthesizing organisms. It is unlikely that mammals would suffer but possibly invertebrates and microorganisms would be affected.

- Ecosystem stability and the geographic distribution of plants, and the animals associated with them, could be affected. Shifts of temperature and precipitation patterns could rearrange the location of major biomes: some species could suffer, others might prosper.

- Special attention should be given to argicultural effects of climate changes. This, of course, is of current concern because climate changes occur naturally but the reaction of the world's food and fiber producing regions to the CO_2-induced climate changes warrants special consideration.

- Much concern has been expressed that warming would cause the polar ice sheets to melt and sea level to rise. It is quite unlikely that this would happen in the next few centuries and may have been overstressed. Climatically-induced surges of the ice sheets are possible but the causes of surges are not well known. It has been asserted, however, that West Antarctica could deglaciate if the ocean should warm and this could produce a 5 meter sea level rise. This possibility deserves some special attention. The recession of mountain glaciers also should be examined although total melting of them would only raise sea level about 1 m.

In the absence of a clear picture of the "new" climate state and the rate at which this state will be approached, it will be difficult to undertake some of the work called for above. Glaciologists cannot say whether the ice sheets will melt until they are advised of temperature and precipitation changes. The same applies to the agriculturalists when contemplating shifts in food production. It will be a long time before there will be agreement about the future climate and a forecast of the consequences will not be very persuasive until then. Rather than wait until this occurs, if it ever does, climate scenarios should be constructed to form a basis for estimating their consequences.

These scenarios, perhaps a half-dozen in number, should span the range of plausible future regional climates should CO_2 continue to increase. They would not be forecasts but the basis upon which speculation of effects can proceed in a rational manner. The scenarios should also include, insofar as possible, measures of year-to-year variability as well as climatic averages. Since the rate-of-change of climate influences the response of the biopsphere and possibly the cryosphere and oceans it should be included in the scenarios. They should be constructed by climatologists in concert with other experts in appropriate fields and be as internally consistent as possible. As climate research proceeds, it should be possible to estimate the likelihood of each scenario occurring.

V. SOCIETAL IMPACTS

The ultimate issue is, of course, the impact of increased CO_2 on society.

This report does not explore the societal effects in any depth but examination of the effects on society of the possible changes is clearly needed and is urgently recommended.

Among the more obvious things to explore are the impacts of shifting agricultural regions and productivity, water availability due to changing precipitation regimes (e.g., can inter-basin transfer of water alleviate the problems of local drought), and impacts on energy demand itself (is there a positive or negative feedback on CO_2 production?).

It must be stressed that impacts of climate change will not fall equally on all segments of the world's society despite their global nature. Indeed some regions or countries may find benefits in the altered climate, others may be relatively unaffected, while some could harmed significantly. Such disparity of effects will make international agreements very difficult to achieve if they are ever needed.

It has been said that if the environmental consequences of increased CO_2 are "unacceptable" the world will have to curtail its use of fossil fuel. It is not likely that an unequivocal and universally accepted prediction of catastrophy due to increased CO_2 will ever be made. The decision to curtail fossil fuel will be made only if and when society's costs of increased CO_2 are believed to exceed the benefits of continued fossil fuel combustion. Achieving world-wide agreement on fossil fuel reduction will present very serious international problems. Thus, it seem worthwhile to explore how societies might cope with the climatic consequences of increased CO_2 rather than hope they can be avoided.

VI. MITIGATING STRATEGIES

Besides reducing fossil-fuel use, one may consider other technological "solutions" should CO_2 increases be seen as undesirable. Certainly both more efficient use of energy and the development of non-fossil energy sources would help reduce the CO_2 growth and could conceivably slow down the arrival or even solve the problem.

None has been proposed so far that seems practicable but this should not deter the search. One should still explore the possibilities of removing CO_2 from effluent streams or from the air, sequestering it in permanent or quasi-permanent reservoirs. Even if such studies fail to uncover a feasible method of doing so they will serve to demonstrate that technological optimism will not substitute for a realistic assessment of the problem.

There will also be those who propose technological controls of the climate itself. Currently, predictions of climate change due to such intervention are too uncertain to be credible. The potential for unforeseen and unwanted climate and other disruptions would be enormous. The ingenuity to devise such schemes might better be focussed on non-fossil energy sources.

APPENDIX A

This material was prepared by William P. Elliott and Lester Machta of the Air Resources Laboratories, NOAA but is based on the efforts of a number of scientists listed below. The Department of Energy provided support to some of the scientists to prepare Research Program Development Papers (RPDP) covering all of the areas discussed in detail in this report. They, in turn, prepared their RPDP with help from a number of colleagues. Two meetings were held in La Jolla, CA (Sept. 1977 and Feb. 1978) of those preparing the RPDP to discuss them. The RPDP, together with the discussion at La Jolla, formed the material from which this document was prepared. A draft of the document was circulated to those who prepared the RPDPs (and to outside reviewers) for comments.

The following contributed to this effort: the appearance of their names here should not, however, be taken to imply their endorsement of everything that appears in this document.

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APPENDIX B

Reading List

A comprehensive bibliography of CO_2-related material would be huge and no attempt is made to present one here. Some recently published compilations of papers given at conferences are listed below: the reference lists in these volumes should provide the reader with an entrance into the recent literature. A useful overview of the CO_2 problem is:

Baes, C.F., et al. (1977): The global carbon dioxide problem. American Scientist, Vol. 65, No. 3, p. 310-320.

Some collections of papers of interest are:

Anderson, N.R. and A. Malahoff, (1977): The fate of fossil-fuel CO_2 in the oceans. Plenum Press, N.Y.

Elliott, W.P. and L. Machta (Eds.) (1978): Report on the Miami Beach Workshop on CO_2, March 1977. To be published by Dept. of Energy, Washington, DC.

Global Atmospheric Research Program (1975): The physical basis for climate and climate modeling. GARP Publ. Series No. 16, WMO-ICSU Joint Organization Com. Geneva, Swtizerland.

Kellogg, W.W. (1977): Effects of human activities on global climate. Tech. Note No. 156, World Meteorological Organization, Geneva, Switzerland.

National Academy of Sciences, (1975): Understanding climate change: A program for action. U.S. Comm. for GARP, Nat'l. Acad. of Sciences, Washington, DC.

National Academy of Sciences (1977): Energy and climate. Nat'l. Acad. of Sciences, Washington, DC.

Singer, S.F. (Ed.) (1975): The changing global environment. D. Reidel, Dordrecht and Boston.

Stumm, W. (Ed.) (1977): Global chemical cycles and their alterations by man. Dahlem Konferunzen, 61.

Woodwell, G.M. and E.V. Pecan (Ed.) (1973): Carbon and the biosphere. U.S. Atomic Energy Commission CONF-720510 (available from Nat'l. Tech. Info. Center).

Some recent technical papers dealing with the carbon cycle and man's role in altering it are:

Adams, J.A.S., et al. (1977): Wood versus fossil fuel as a source of carbon dioxide in the atmosphere. _Science_ 196, p. 56.

Bolin, B. (1977): Changes in land biota and their importance for the carbon cycle. _Science_ 196, p. 613

Siegenthaler, U. and H. Oeschger (1978): Predicting future atmospheric carbon dioxide levels. _Science_ 199, p. 388.

Stuiver, M. (1978): Atmospheric carbon dioxide and carbon reservoir changes. _Science_ 199, p. 253.

Wong, C.S. (1978): Atmospheric input of carbon dioxide from burning wood. _Science_ 200, p. 197.

Woodwell, G.M., et al. (1978): The biota and the world carbon budget. _Science_ 199, p. 141.

APPENDIX C

Estimated Funding

Presented here in tabular form is a summary of the estimated dollar amounts (1977) needed to support the recommended programs in carbon cycle and climate modeling research. The two columns, initial requirements and full-scale support, are taken from the text. The approximate nature of these estimates cannot be overstressed, particularly for the full-scale support. No account is made for general inflation because the estimates are too crude but should the program last for many years, it is likely more money than given would be needed later. Also some savings could be achieved by combining some of the efforts, particularly, in the oceanic work recommended. Until such time as some of the recommended feasibility studies have been carried out, the sums recommended for the expensive large-scale programs can only be considered educated guesses.

Estimated Annual Funds (1,000s of 1977 dollars) Required for Program

Subject	Initial Amount	Full-Scale Program
Net Sources to Atmosphere		
Industrial sources	50	500
$^{13}C/^{12}C$	250	600
Direct estimate of biomass	175	3000
Soil carbon	175	400
Inorganic terrestrial carbon	50	200
Synthesis of biosphere	50	50
TOTAL	750	4750
Atmospheric Storage		
Monitoring networks	270	170
Standard gases	100	100
Instrumentation	100	100
TOTAL	470	370
Oceanic Sinks		
Air-sea gas exchange	50	200
Buffer factor	200	300
Inorganic transfer within ocean	50	5000
Organic transfer within ocean	60	1000
Shallow water sediment dissolution	50	1000
Deep water sediment dissolution	50	1000
TOTAL	460	8500
Terrestrial Sinks		
Response of biota	50	1000
Modeling of carbon cycle	30	200
TOTAL	80	1200
Climate Changes		
Modeling future climate	250	1000
Reconstruction of past climate	100	200
TOTAL	350	1200
GRAND TOTAL	2,110	16,020

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