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Assistant Secretary for Environment
Office of Health and Environmental Research

Carbon Dioxide Effects Research and Assessment Program

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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Carbon Dioxide and Climate Division
Office of Health and Environmental Research
Department of Energy

Preface

Initial plans for research of the carbon dioxide (CO_2) and climate issue were prepared in 1978 and were reviewed extensively at that time by federal agencies and members of the scientific community. Since then the plans have been used to guide early phases of the Department of Energy's and the nation's efforts related to this issue. This document represents a revision of the 1978 plan to (a) reflect recent ideas and strategies for carbon cycle research, and (b) expand the scope of research on climatic responses to increasing atmospheric concentrations of CO_2. The revised plan takes into account a number of investigations already being supported by various agencies, and it attempts to build on or add to existing research where there is a crucial need for information directly related to the CO_2 issue. It should be recognized that this document is the first section (Part I) of a comprehensive plan on the overall consequences of increasing concentrations of CO_2, and includes guidelines for research on the Global Carbon Cycle and Climatic Effects of Increasing CO_2. A second section of the comprehensive plan (Part II), related to the Environmental and Societal Consequences of a Possible CO_2 Induced Climate Change, is in preparation. Also in preparation is a Plan for a National Program on Carbon Dioxide, Environment and Society which outlines institutional management and interagency coordination required for a national CO_2 program. The three documents collectively will provide valuable guidance to both national and international program sponsors and to the scientific community for investigating what is believed to be a very crucial environmental issue related to global energy use.

The revised Part I Plan is based on (a) the results from a number of topical workshops, (b) in-depth review and discussion of issues at a research progress meeting (April 23, 24, 1980), (c) ad hoc contributions from interested scientists, and (d) a reexamination of the issues by Drs. Lester Machta, William Elliott and Michael MacCracken. Drs. Murray Mitchell and Fred MacKensie summarized the main scientific concerns which emerged from the April Research Progress Meeting, and Dr. Roger Dahlman of this Office fostered completion and review of the revised plan. The efforts of all who contributed are deeply appreciated.

David H. Slade, Director
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Office of Health and Environmental Research
Office of Environment

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THE CARBON DIOXIDE ISSUE

The perception that accumulations of atmospheric CO_2 may result in serious problems stems from the following:

- There has been a well-documented worldwide increase in atmospheric CO_2 concentrations since 1957; this growth has probably been occurring since the middle of the past century.
- During the past few decades, the CO_2 increase in the atmosphere has equaled about 50 percent of the total 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 and reradiates part of it back to warm the surface of the earth, creating the so-called "greenhouse" effect. Thus, qualitatively, CO_2 should warm the lower atmosphere. The redistribution of radiative fluxes also tends to cool the stratosphere.
- Different calculations of the greenhouse warming indicate that a doubling of the CO_2 content of the air could result in a $3 \pm 1.5°C$ warming of the lower atmosphere. This global warming would be a significant alteration of the present climate, to a degree unprecedented in historical times.
- While such climatic effects would be worldwide, they would likely not be geographically uniform: some regions of the globe would experience greater changes than others.
- The doubling of atmospheric CO_2 is likely to occur during the middle of the next century if use of fossil fuel continues to grow. There are sufficient fossil-fuel reserves to raise the atmospheric CO_2 severalfold, if they are used.

- The natural removal mechanisms are such that it will likely take many centuries before anthropogenically induced high CO_2 concentrations in the atmosphere return to "normal" levels after the additions cease.
- Present-day concepts of environmental control technology of CO_2 do not appear feasible from economic and energy requirement standpoints.

At this time, scientists are not absolutely certain that significant climate changes will occur if the burning of fossil fuel continues or that the predicted climate change would, on the whole, be adverse. On the other hand, all climate changes will impose stress and we cannot ignore the possibility of long-lasting undesirable climate changes. It is imperative that society be able to anticipate the consequences of fossil fuel consumption and CO_2 release.

Answers to the following questions should be obtained in order to evaluate possible courses of actions.

1. What will be the future atmospheric concentrations of CO_2 for various scenarios of carbon dioxide releases to the atmosphere?
2. What will be the climatic response to these elevated CO_2 concentrations?
3. How will these climate changes, along with the increased CO_2 concentrations, affect the geological and physical environments?
4. What, if any, will be the effects of these changes on human societies?

5. In the event these changes are undesirable, what actions can be taken to prevent or counteract them? Or to improve adaptation to them? If the changes are locally beneficial, how can these regions be identified?

This document will lay out research plans to seek answers to the first two of these questions. The plan, originally developed in 1978 for limited distribution, drew heavily on the results of a Department of Energy-sponsored workshop held in Miami Beach in March 1977 (Elliott and Machta, 1979), the National Academy of Sciences publication Energy and Climate issued in late 1977 (Geophysics Study Comm., 1977), and a number of national and international workshops held during the past few years. This revision was reviewed in April 1980 by a group of scientists and many of their comments are reflected herein.

The United States carbon cycle and climate research program must be considered in the context of an international research program. Two examples may suffice to demonstrate the importance of the international aspects of the carbon cycle issue. First, carbon storage and release in tropical areas can be greatly affected by the deforestation now taking place. The countries in which such biospheric changes are likely will be encouraged to supply information and to cooperate with developed countries in providing ground truth for satellite observations, etc. Second, the oceans are the ultimate sink for fossil fuel carbon. The vast area dictates that ships from many countries are needed to make measurements jointly; the task is likely too large for the U.S.A. alone.

At present international leadership is shared between the International Council of Scientific Unions (ICSU), representing the academic world, and the World Meteorological Organization (WMO) for the governments. ICSU has delegated the responsibility to its Scientific Committee on Problems of the Environment (SCOPE) which, in turn has set up a special working group on carbon dioxide. Carbon dioxide related research is also carried out by national governments such as the Federal Republic of Germany, Australia and Sweden. As international interest in resolving the uncertainties in the CO_2 issue grows, countries beyond those in the developed world will likely participate.

I. THE GLOBAL CARBON CYCLE

The atmosphere, the ocean and the biosphere are the three major components of the exchangeable carbon cycle (Figure I.1.). Note that except for the atmosphere the amount of carbon in each reservoir is somewhat uncertain; the individual fluxes between and within reservoirs are even more uncertain. The mathematical description of the carbon cycle permits prediction of the fate of new CO_2 added to the atmosphere but such forecasts are currently flawed because of the uncertainties illustrated in the figure. An extensive treatment of the carbon cycle can be found in Bolin et al. (1979).

Predictions of future levels of CO_2 in the air will ultimately be made by improved numerical models of the carbon cycle. To successfully model the carbon cycle will require better information on (a) net fluxes of CO_2 between various reservoirs--with particular attention to emissions from anthropogenic sources; (b) observation of atmospheric CO_2 and its changes with time and space; (c) studies of past atmospheric CO_2 concentrations; and (d) integrated models of the carbon cycle which can predict changes due to man-made CO_2 sources. The principal research issues of the carbon cycle category are summarized in Figure I.2. Priority and summary budget recommendations are presented in Table I.1.

A. Fluxes of Carbon Dioxide

A major source of the observed increase in CO_2 is the combustion of fossil fuels. Recently, however, the possibility has been raised that world-wide land use practices, particularly deforestation in the tropics, could also be contributing to the buildup (Woodwell et al, 1978). Both types of fluxes are expected to increase in the future. It is widely accepted that sources such as volcanoes and other venting of gases from the

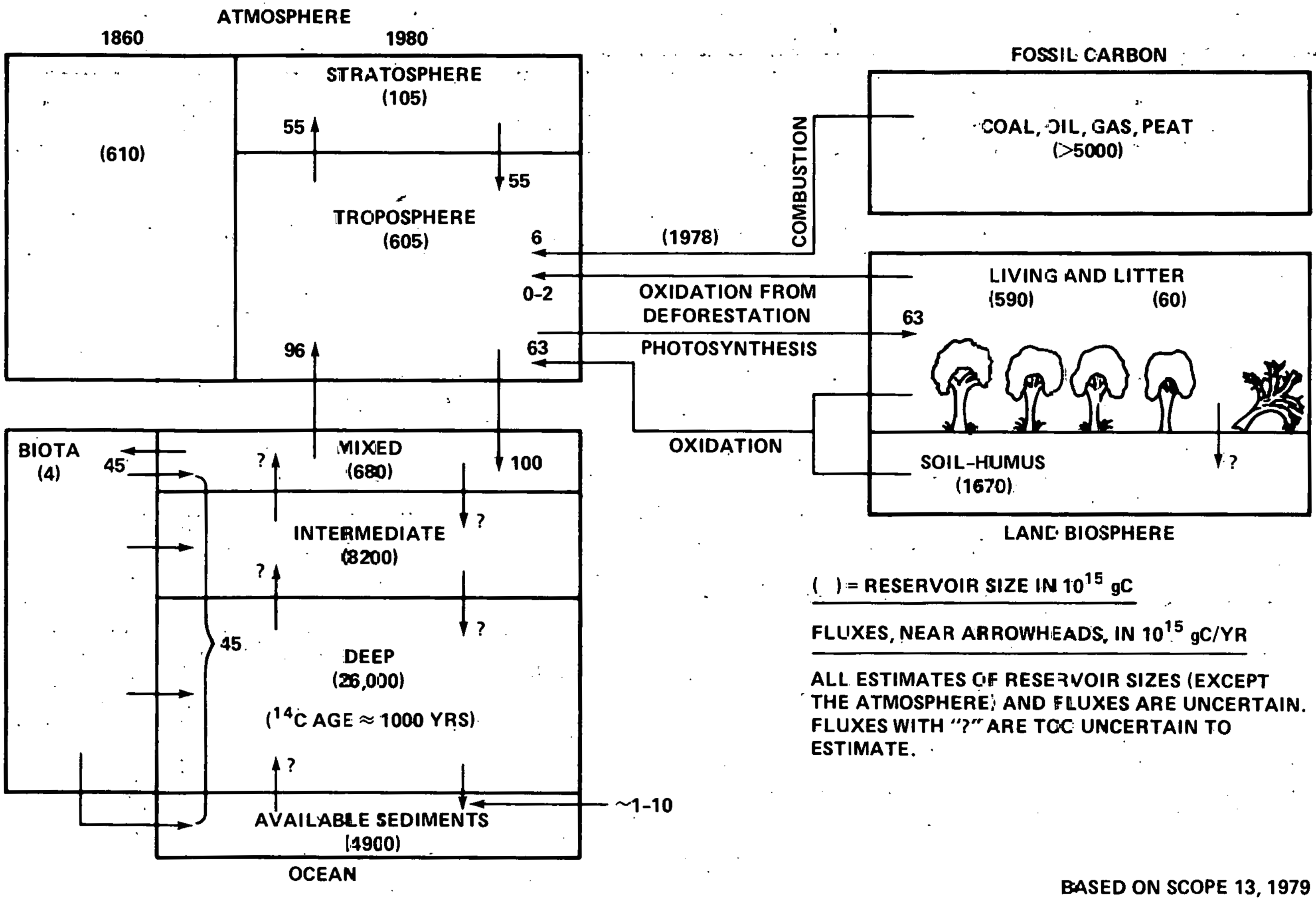

FIGURE I.1. Exchangeable Components of the Global Carbon Cycle

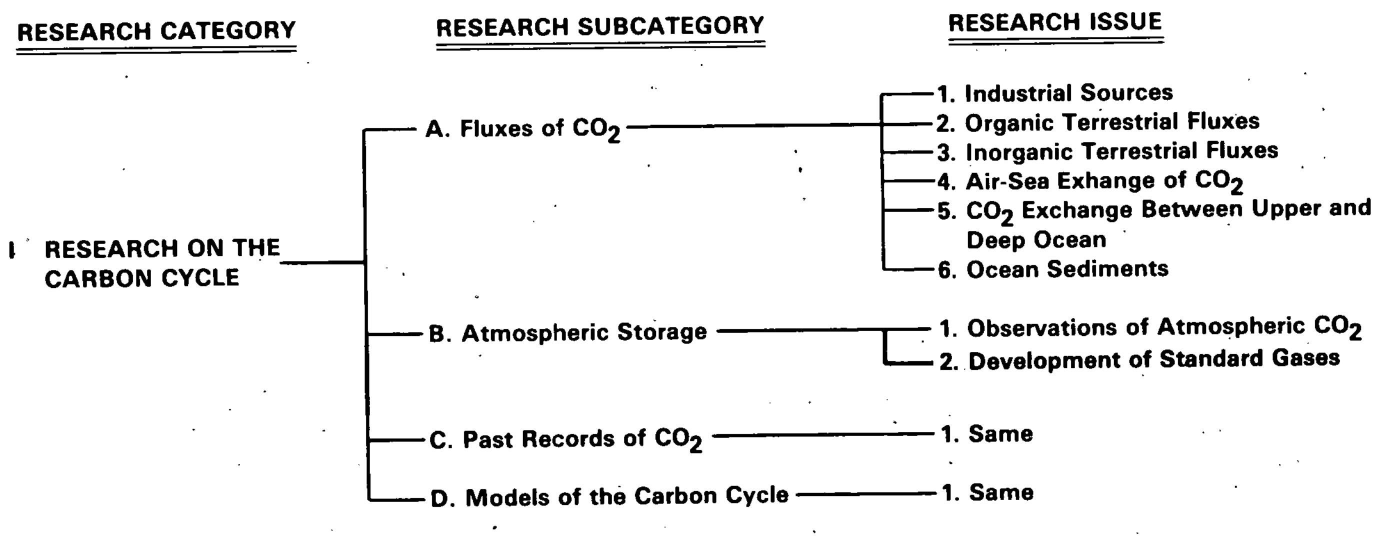

FIGURE I.2. Principal Research Issues of the Carbon Cycle Program Plan

TABLE I.1. Summary Budget and Priority Recommendations for Carbon Cycle Research

Research Subcategory	Research Issue	Priority	Recommended Budget* Fiscal Year 80	81	82	83	84
CO_2 Fluxes	Industrial Sources	Medium to High	200	200	250	250	250
	Organic Terrestrial Sources	High	700	1500	2500	3000	3000
	Inorganic Terrestrial Sources	Medium	0	100	100	200	200
	Air-Sea Exchange of CO_2	Low	200	250	300	300	300
	CO_2 Exchange-Upper/Deep Ocean	Medium to High	2000	2200	1500	1500	3000
	Ocean Sediments	Low to High	15	200	200	200	200
Atmospheric CO_2 Storage		High	100	350	350	350	350
Records of CO_2		Low to High	280	350	350	350	350
Models of Carbon Cycle		High	300	400	400	750	750
TOTAL			3795	5550	5950	6900	8400

* Budget amounts are in $1000s. Amounts for FY 1980 are approximate expenditures; amounts for outyears are projections required for a balanced sustained program. This interpretation applies to all budget data shown in all successive tables of this document.

interior of the earth, while important over the long history of the earth, are not a significant factor in the recent rise (Baes et al, 1976). Scattered observations in the late 19th and 20th centuries suggest a CO_2 concentration only 10-20% lower than today's value. Further back in time, there is little information on the concentration or fluctuations that would shed light on natural sources of CO_2.

It is important to determine the relative importance of fossil fuel and biospheric emissions. If the expected impacts of increasing CO_2 ever point to the need for control of the sources of atmospheric CO_2, curtailment of fossil fuel usage might not be the only action required.

In addition to determining the magnitude of net sources, the processes removing CO_2 from the air must also be understood. Obviously, a prediction of the future atmospheric concentration of CO_2 depends on all fluxes into and out of the earth's atmosphere.

1. Industrial Sources

Projections of future releases of CO_2 from fossil fuel combustion are the most important first step in assessing the future impacts of increasing CO_2 on man and his environment. Continued increases in emissions could set the stage for an imminent problem while reduced emissions could delay the need for further studies of the carbon cycle, climate, and impacts of the CO_2 issue. Knowledge of past releases of CO_2 is also needed for the validation of carbon cycle models.

There are three aspects of industrial sources of CO_2 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 now converted to fuel and used (also other industrial sources such as cement

Table IA.1. Priority, milestones and estimated budget requirements for research on industrial sources.

Priorities:

Maintaining a record of past and current emissions of industrial fossil fuel sources of CO_2. Improving the accuracy of the estimates. The maintenance of the emission record is relatively easy to perform and will be done virtually irrespective of its priority.	Medium
Preparation of future world energy scenarios and projected releases of CO_2. This function will be performed mainly for other reasons and by organizations funded by non-CO_2 related programs. Special scenarios for the CO_2 issue will be needed for sensitivity studies, etc.	High

Milestones and Budget:

Fiscal Year	Milestones	Budget
1980	Review published energy scenario predictions, update past and current CO releases.	200
1981	Initiate energy scenarios focused on updating past and current CO_2 releases.	200
1982	Issue report on future energy scenarios related to CO_2 issue, update past and current CO_2 releases.	250
1983	Analyze and improve knowledge of sources of past and current CO_2 releases. Prepare draft summary report.	250
1984	Issue a revised future scenario report, assist in preparing a CO_2 status report, update past and current CO_2 releases.	250

production); and perhaps most important, projection of future demand for these fuels (Geophysics Study Comm., 1977).

The available reserves are well enough known today to argue that, if burned, atmospheric CO_2 will likely increase to several times its present concentration. Better assessment on a country-by-country basis will be needed to keep track of current use and estimate future levels of combustion. The carbon content varies among and even within each type of fuel. The carbon content and energy equivalent of each fuel source, including the synthetic fuel cycle, must be examined before their CO_2 potential can be accurately assessed.

The actual rate of fuel consumption must be monitored (and converted to CO_2) to determine the current annual emissions. It is not always easy to estimate this on a global basis because of the varying quality of the international data base. Countries may distort their fuel production and usage for internal reasons so cross-checks must be made. Although global data on fuel production and consumption are available from the United Nations, the conversion to CO_2 releases requires knowledge of the carbon content of each fuel, a parameter that is not always available.

Future emissions of CO_2 into the atmosphere are difficult to estimate, depending as they do on a variety of socio-economic factors and political considerations. Various extrapolations can be made based on historical consumption rates and population growth rates broken down by country or region, but these need constant checking and updating. Such factors as limitations on capital, environmental considerations, and availability of foreign exchange can influence a country's use of fuel. The energy contribution from fossil fuels will also depend on the availability and cost of alternative energy sources. More detailed and realistic estimates of future use of fossil fuels, considering all the possible constraints on their use, should be undertaken.

2. Organic Terrestrial Fluxes

A controversy exists as to whether net changes in biomass* from deforestation and other land-use practices are now a net source of atmospheric CO_2 or whether the biosphere has recently been acting as a net sink of atmospheric CO_2. Current models of oceanic uptake of CO_2 are in better agreement with the atmospheric increase of CO_2 if, at most, only a small net amount of CO_2 is coming from the biosphere. Yet some evaluations of biomass data indicate that net biomass changes contribute amounts of CO_2 equal to or greater than the fossil fuel contribution itself. If the latter has been the case over the past 20-100 years, then the sinks for atmospheric CO_2 must be seriously underestimated by the current models.

Regardless of current and past trends in the biomass carbon reservoir, future emissions of CO_2 could be substantially increased by large-scale forest clearing followed by the oxidation of the material and soil humus. There is little known about current or past rates at which land vegetation has been altered or removed, with consequent changes in stored carbon. The conversions can be deliberate, e.g., conversion of the forest areas to agriculture; incidental to other activities; or they may be natural as a result of local climatic shifts. Other deliberate or natural conversions can also

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* As used in this document, the term "biomass" refers to both living and dead organic matter of recent origin; i.e., it excludes fossil fuels.

Table IA.2. Priority, milestones and estimated budget requirements for research on organic terrestrial fluxes.

Priorities:

Determination of net flux of CO_2 from the biosphere is a very high priority item. The first step is to investigate the feasibility of several of the proposed methods. Subsequent priorities will depend on the outcome of these feasibility studies. It is planned to pursue more than one line of research.

1.	Carbon isotope studies to remove some of the uncertainties in the interpretation of the $^{13}C/^{12}C$ ratios in tree rings, coral rings, and present atmosphere.	High
2.	Precise measurements of changes in atmospheric O_2.	High
3.	Detection of changes in CO_2 (inorganic carbon) in the oceans.	High
4.	Measurement of carbon changes in terrestrial biomass and soils by satellite sensing and/or in-situ observations.	High
5.	Responses of biota to increased atmospheric CO_2.	High

Milestones and Budget:

Fiscal Year	Milestones	Budget
1980	Determine feasibility of items a.-d.; begin collection of samples for O_2, continue work, previously started, for items a. and c.	700
1981	Select methods for intensive effort. Begin measurement phase.	1500
1982	Continue measurements.	2500
1983	Continue measurements. Assess results and desirability and need for using other approaches. Prepare draft summary report.	3000
1984	Continue measurements. Complete summary report on findings to date.	3000

increase vegetative CO_2 uptake.* One must estimate the changes in biomass both to formulate and calibrate models of the carbon cycle as well as to predict the effect on atmospheric CO_2 of future land-use changes.

A change of less than 0.5% in total biomass, if converted to CO_2, would be equivalent to the current annual fossil fuel additions. The required precision for detecting such a small biomass change will tax the ingenuity of the scientific community.

A number of methods have been suggested for determining the net amount of CO_2 added to (or subtracted from) the atmosphere by the biosphere. These include some indirect methods such as measurements of the ratio of carbon isotopes in tree rings and the air, measuring the changes in O_2 in the air, measuring changes in CO_2 in the atmosphere and oceans, and direct measurements of changes in biomass. A discussion of these approaches follows.

2.1 The $^{13}C/^{12}C$ method of determining biomass changes

Organic matter in vegetation and humus is depleted in ^{13}C because photosynthesis fractionates absorbed atmospheric CO_2. When the carbon is oxidized after the vegetation dies, the CO_2 that is returned to the atmosphere is therefore enriched in ^{12}C relative to that in air. Fossil fuel carbon is similarly depleted in ^{13}C. By measuring the decrease of $^{13}C/^{12}C$ in air with time, one can detect deforestation and other oxidization of biomass by subtracting the expected decrease due to fossil fuel combustion from the decrease observed in the air. Programs for the measurement of $^{13}C/^{12}C$ have begun and should be expanded.

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* For example, a large area of interior Australia has been transformed, at least temporarily, from desert to savannah because of increased rainfall during the past 5-6 years.

However, the scientific community has exhibited considerable interest in using tree rings (and, to a lesser extent, coral rings) as proxy indicators of atmospheric $^{13}C/^{12}C$ ratios of the past. Studies of tree rings have raised a number of unexpected uncertainties. To date trees in different geographical areas have provided different time trends in the $^{13}C/^{12}C$ ratio. A group of scientists believe that the $^{13}C/^{12}C$ trends reflect environmental conditions (e.g., climatic changes and local pollution) rather than or in addition to changes in atmospheric $^{13}C/^{12}C$ ratio. There is also uncertainty concerning the magnitude of the fractionation effect of $^{13}C/^{12}C$ during photosynthesis. The expected $^{13}C/^{12}C$ ratio in trees is therefore uncertain. The reported $^{13}C/^{12}C$ trends in coral fail to parallel those of tree rings.

Finally, measuring trends in the $^{13}C/^{12}C$ ratios from past records represents only the first step in the estimation of biomass changes. The history of the change in $^{13}C/^{12}C$ from biomass releases and fossil fuel combustion must be understood in terms of a model of the carbon cycle in such a way as to provide agreement with the observed trend in $^{13}C/^{12}C$. These steps have proven to be more than trivial. It has been shown, for example, that between 1958 and 1978, the $^{13}C/^{12}C$ ratio measured in air agrees equally well with carbon histories either including or excluding deforestation.

A number of investigators are continuing their study of the measurement and interpretation of $^{13}C/^{12}C$ ratios in tree rings. It is expected that factors such as pollution and climate effects and fractionation uncertainties can be resolved within a few years. The trees selected for analysis should have experienced minimal or known environmental changes and insofar as possible reflect conditions in the non-forest atmosphere. A number of organizations are already sampling ambient clean air for $^{13}C/^{12}C$ analysis. Further, sources of old air in ice cores may prove to be valuable and might extend the CO_2 record backward beyond historical epochs either by direct measurement of CO_2 concentration or through the measurement of $^{13}C/^{12}C$ ratios. A review of the status of stable isotope research will be available soon (Jacoby, 1980).

The $^{13}C/^{12}C$ method for measuring biomass change still shows promise. There is reason to expect the problems can be solved in the next few years. The method deserves support but alternative techniques must also be actively pursued.

2.2 The oxygen method

When carbon is oxidized to CO_2, the two oxygen atoms come from the atmosphere. If the decrease of atmospheric O_2 can be measured and the portion attributed to the combustion of fossil fuel is subtracted, the remaining decrease could be assumed to be due to the formation of CO_2 from all other sources. These latter sources would include oxidation of biomass carbon as well as the oxidation of reduced sulfur and ferrous iron. Evidence points to carbon oxidation as, by far, the dominant way in which oxygen would be lost from the atmosphere. Thus, one potential means of measuring the CO_2 emissions from biomass loss is by measuring changes in atmospheric oxygen.

The advantage of the technique lies in the ability to provide global average values of non-fossil fuel CO_2 sources. This advantage becomes a defect if one wishes to know where the biomass changes are taking place. Its main shortcoming lies in its demand for measurement accuracy beyond what is now possible. If one wishes to detect amounts of CO_2 equal to about 10% of the current fossil fuel source in only a few years, one must compare two numbers whose difference lies in the sixth or seventh significant figure. Today, one can achieve the fifth or possibly the sixth significant figure. (This is discussed more fully in Jacoby, 1980).

There are several possible techniques to reach the very high precision demanded by the oxygen method including an improved paramagnetic apparatus, (Machta and Hughes, 1970), developing a gravimetric method, (Schwiesow and Derr, 1970) and an isotope dilution procedure. These ideas should be explored and the more promising ones developed, if feasible. A first step could be the immediate collection and careful storage of air samples so that air will be available when the analysis techniques are available.

Besides the instrumental difficulties, it must be determined that biomass oxidation and fossil fuel combustion are the only significant contributors to changes in atmospheric O_2. Because of the very small changes involved, great care must be taken to insure that any measured changes, or lack thereof, are properly interpreted. Of particular concern are changes in the exchange rate of O_2 across the air-sea interface. Thus the feasibility of this technique must be confirmed by examining more carefully other oxidizing processes and the air-sea chemistry.

2.3 Change in atmosphere-ocean carbon inventory

The increase in concentration of atmospheric CO_2 must appear as the sum of the changes in the several exchangeable carbon reservoirs. Existing and planned national and international atmospheric monitoring programs can accurately document the increase in the CO_2 concentrations in the air. By carefully measuring the increase in the total inorganic carbon of the oceans, one has the sum of the two non-biospheric reservoirs. When the fossil fuel CO_2 is subtracted from the sum of the changes in the two reservoirs, the residual represents the increase or decrease of the biosphere.

The percentage change in atmospheric and oceanic CO_2 will be very small. For example, the current increase in the air is of the order of 0.5% per year. Because of its much larger carbon content, the percentage changes in the oceans will be much smaller. The increase in the air is measurable since the atmosphere is relatively homogeneous and measurement techniques are precise to about 0.1%.

There are obvious difficulties in measuring the inorganic carbon inventory of oceans. For example, the number of oceanic samples needed to obtain a reliable inventory of total inorganic carbon is unknown and is expected to be large. It is possible that relating total inorganic carbon measurements to other, more numerous, measurements of chemical and physical properties of the ocean, the sampling requirements for total inorganic carbon measurements can be greatly reduced. The small expected change demands high precision. As of this writing, accuracy of the order of 1 part in 4000 is only in the developmental stage in one laboratory. While there is reason to expect the techniques could become routine, this accuracy pushes the state-of-the-art.

The atmosphere-ocean carbon inventory method is being pursued and, until shown to be unsatisfactory, will be supported.

2.4 Direct estimates of biospheric changes

Direct estimates through surveillance and other means of the changes in carbon stored in the terrestrial biomass, mainly in the world's forests, require determination of changes in both the carbon content of living matter and the carbon stored as dead organic matter. This is very difficult and will require careful evaluation to determine if estimates can be obtained with the required accuracy in a cost effective manner. This method was the subject of a major DOE-sponsored SCOPE Workshop May 7-11, 1979 in Woods Hole, MA. The proceedings (Woodwell, 1980) will elaborate the virtues and limitations of this direct method.

2.4.1 Changes in living organic carbon pools

A good deal of evaluated data on the living biomass already exist at locations scattered around the world. These data should be located, cataloged, and synthesized into histories of changes in the living vegetation of the world over the past centuries.

Remote sensing may be the most feasible way of monitoring future changes in living carbon reservoirs but this technique will have to be verified by substantial "ground-truth" measurements. The first step must be a study of its feasibility. Thorough consideration must be given to a sampling strategy with proper statistical considerations. Global monitoring of the biosphere will be costly, time-consuming, and difficult with no assurance of success.

The concept, in principle, is straightforward. Imagery from the Landsat satellite (including Landsat C and D) could be used as the basis for the construction of a global vegetation map. Difficulties will arise because substantial changes in vegetation type occur over short distances. There will also be difficulties in definition of soil characteristics and in choosing the appropriate spatial resolution. In some tropical areas, prevailing cloudiness prevents suitable ground viewing. High resolution radar, aerial photography, and ground surveillance may be required to supplement satellite data.

Such a global map could, however, provide measurements of the areal distribution of vegetation. Converting these measurements to stored carbon and change in carbon will be even more difficult. Many ground surveys would be required, in a wide variety of regions. The best solution may be a combination of remote sensing with selected in situ measurements. Landsat pictures have already detected deforestation in small areas of the tropics. No studies have yet investigated reforestation. Nor has there been any study of how to convert visible forest changes to changes in carbon content.

It is suggested that any technique to measure biospheric sources of CO_2 should be accurate to better than 20% of the current fossil fuel emissions (i.e., better than about 1×10^{15}gC). It was argued in Woods Hole in May 1979 that this amount of carbon represents an upper bound of non-fossil fuel CO_2 which could be accommodated by existing, albeit imperfect, carbon cycle models. The living biosphere contains about 600×10^{15}gC. Thus, the desired accuracy must be of the order of 0.1%, an almost impossible accuracy to achieve by estimating vegetative carbon at two successive times by surveillance. Most suggestions for using aerial surveillance for detecting changes in the living biosphere on a global scale thus far appear to be very costly, time consuming, and require small scale feasibility studies before embarking into the global scale. New ideas are needed to avoid these difficulties.

2.4.2 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 uncertain how much of this carbon readily exchanges with the atmosphere or how much could be released to the air when the soil or the vegetation is disturbed. 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.

The problem of estimating changes in soil carbon on a world-wide basis is extremely difficult, even more so than for the living biomass. It may not be possible to estimate, with sufficient accuracy, net contributions to atmospheric CO_2 in the past. It will still 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 (e.g., charcoal) unlikely to be disturbed by man's activities or unable to enter the atmosphere. The amount of living material converted to refractory carbon by burning needs to be determined.

One approach is to assess age and turnover time of the organic fractions that contribute to the carbon content of soils. The goal of this research would be an estimation of the extent to which man's activities have affected releases of carbon from soil organic matter of various ecosystems. Another research aspect is the transfer of carbon between soil layers and into solution. Some help in these matters can be expected from ^{14}C ages but roots of living material may transfer carbon to deep soil horizons, thereby complicating the problem.

Special attention should be paid to peat regions, bogs, and other wetlands. Although not great in total area (about 1% of the area of the earth), the primary productivity of these regions is large (over 7% of the world carbon production), 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 dioxide to the air as well as reduce the annual carbon fixation of these regions.

2.5 Response of biota to increased atmospheric CO_2

Some models of the carbon cycle assume that the excess CO_2 enhances photosynthesis. Some commercial crops have shown increased yields when grown in greenhouses at elevated CO_2 concentrations (up to 1000 ppm). It is not yet clear, however, that similar results would occur under natural conditions where water, sunlight, temperature and nutrients might be limiting factors to increased growth. Despite this uncertainty, many if not most of the current carbon cycle models incorporate a fertilization factor for higher concentrations of CO_2. Typically it is argued that a given fractional increase in CO_2 concentration increases CO_2 uptake by the biota, mainly the world forests, but that only a fraction of the forests are capable of responding to CO_2 fertilization.

While the main question is the amount of enhanced biospheric storage of carbon, increased CO_2 could also 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 unidentified 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 recommended environmental effects research program 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 and, of course, actual growth. Photosynthesis is the central process governing the primary productivity of all green plants. The availability of nitrogen 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 behavior of the stomata, which in turn may be influenced by elevated ambient CO_2 concentration. It is possible that increased atmospheric CO_2 could result in improved 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. 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 carbon in biomass or detritus will it increase the strength of the sink for excess CO_2.

Even if plants sequester more carbon in response to increased ambient CO_2, it must be determined if heterotrophic respiration will return the CO_2 to the atmosphere. If this occurs on a short time scale, little additional carbon will be stored in the terrestrial biosphere.

A research program on biotic response to increased atmospheric CO_2 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 CO_2 levels).

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 under controlled conditions.

5) Studies of the effect of chronically increased CO_2 on growth. These include rates 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. A major part of this research should be conducted at natural field sites, located in different biomes and latitudes. Controlled growth experiments with enhanced CO_2 in simulated natural environments, possibly using naturally illuminated greenhouses, should also be studied for feasibility. An alternative to growth chamber studies is the bathing of selected, possibly forested, plots with locally generated CO_2. The problem of knowing the magnitude of the greater CO_2 concentration around the trees, etc., may be overcome by sampling the air for CO_2 concentrations at a number of places on the sites. It has been suggested that the released CO_2 be given a different $^{13}C/^{12}C$ ratio than the air. This anomalous ratio could then be measured in the material which has been grown and the uptake of locally introduced CO_2 inferred. The feasibility of this idea is being examined.

6) Conceptual and mathematical models relating the various responses of photosynthesis, growth, and ecosystem respiration, to increased CO_2. These models should be continually developed and updated as the data base increases. The final goal is the construction of reliable <u>predictive</u> models of the overall effect on global productivity and storage of excess CO_2.

3. Changes in Inorganic Terrestrial Carbon

The size of the inorganic terrestrial carbon pool and its dynamics are less well known than organic carbon pools. The possible role of this pool in exchanging carbon with the other reservoirs on the time scale of a few years to decades is also not well understood. Of the carbonate minerals exposed on the land surface, calcitic and dolomitic type minerals contain over 1600 x 10^9 tons of carbon in the first meter of soil. A large fraction of this pool is not readily available for solution. But changes in carbonates do occur with irrigation and with modifications of climate and vegetation. Calcareous soils in humid regions have less carbonate but the turnover is faster. It is not clear whether the inorganic carbon constitutes a source or sink of atmospheric CO_2. A preliminary study of the magnitude of the carbonate pool and its chemical dynamics, including its role in controlling atmospheric $^{13}C/^{12}C$ ratios would define whether more detailed research should proceed. Other aspects likely to need study are deep leaching of bicarbonate, recycling of fossil ground water saturated with carbonates, the influences of acid precipitation, agricultural liming (fossil carbon) of acid soil, and the significance of apparent imbalances in global cycling of calcium.

4. Air-Sea Exchange of CO_2

It would appear that the exchange of CO_2 between air and ocean water should be crucial to the prediction of the amount of fossil fuel CO_2 that remains in the air. However, empirical evidence indicates that this exchange is sufficiently rapid, on a time scale of years, so that its exact value, while valuable, does not significantly alter predictions of atmos-

Table IA.3. Priority, milestones and estimated budget requirements for research on inorganic terrestrial fluxes.

Priorities:

To establish the role of exposed carbonate rocks and calcareous soils some preliminary estimates of the magnitude of these pools and fluxes to and from the air are needed.	Medium

Milestones and Budget:

Fiscal Year	Milestones	Budget
1980	None.	
1981	Initiate preliminary studies.	100
1982	Determine the need for further efforts.	100
1983	Continued effort if required. Prepare draft summary report.	200
1984	Evaluate current studies.	200

Table IA.4. Priority, milestones and estimated budget requirements for research on air-sea exchange of CO_2.

Priorities:

Some continuation of the present investigations of transfer across the air-sea boundary is planned. Much of the work would be incidental to other oceanic observations. Direct measurements of fluxes should be investigated briefly for its feasibility. The investigations have a low priority except where they can be carried out easily and with relatively little expanse in connection with higher priority items.	Low

Milestones and Budget:

Fiscal Year	Milestones	Budget
1980	Assess the need for special flux measurements over the sea. Obtain CO_2 gradient measurements across the air-sea interface on ships of opportunity.	200
1981	Measure fluxes with either special equipment and/or by air-sea gradients on ships of opportunity. Initiate study of all information bearing on the rate, the diurnal and seasonal, and the geographical variations of CO_2 exchange across the air-sea interface.	250
1982	Continue flux measurements and study existing information.	300
1983	Continue flux measurements. Prepare a comprehensive report on knowledge about the air-sea exchange.	300
1984	Reassess the needs for further measurements and analyses.	300

pheric CO_2 concentrations for periods of decades to centuries in the future. The value of further research in air-sea exchange derives more from an understanding of its geographical distribution and physical processes rather than for future CO_2 predictions in air. As such, the urgency of research is reduced at this time.

The techniques can be categorized in three ways: methods that measure quantities at or near the air-sea boundary, those dependent on oceanic measurements, and those dependent on atmospheric measurements.

The near-sea-surface measurement methods include: the use of modern eddy-correlation techniques at selected points, the only direct method of measurement of the vertical flux of CO_2; the profile method, which assumes that the flux can be derived from the gradient of a measured CO_2 concentration by multiplication by an eddy diffusion coefficient that is often known very imperfectly; the air-sea profile method, which calculates the flux by multiplying the air-sea CO_2 concentration gradient and an imperfectly known transfer coefficient; and controlled laboratory simulation of the transfer of CO_2 between air and ocean water (e.g., relating uptake via wind speed and air-sea gradient). All of these methods have been reported upon, although not necessarily quantitatively.

The measurement methods in air include: the Suess effect, which refers to the dilution of $^{14}CO_2$ by fossil fuel CO_2; the decrease with time of $^{14}CO_2$ generated in nuclear weapons tests as it enters the biosphere and oceans; and global meridional gradients of CO_2 that are fitted to sources and sinks of CO_2 into and out of the air. These methods have also been tried and reported upon.

The oceanic measurement methods include: inferences about air-sea transfer based on transport of radon; the measurement of increases of total inorganic carbon in the ocean with time and the increase of CO_2 in air; and vertical flux measurements in the upper layers of the ocean. The radon method has been often reported in the literature; work is in progress to develop the total inorganic carbon method, but there is little or no effort in the measurement of downward flux through the ocean.

The buffer factor represents the ratio of the fractional change in pCO_2 (the partial pressure of CO_2) in the air to the fractional change of pCO_2 in the water at chemical equilibrium. Its value is currently estimated to be between about 7 and 11, depending on the temperature. The values calculated from thermodynamic principles seem to be generally accepted but a small program to measure the values in situ is being undertaken to insure that no discrepancies between theory and measurement exist.

5. CO_2 Exchange Between the Upper and Deep Ocean

5.1 Transfer of inorganic carbon in 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 (detritus).

Planning for research in calculating the transport of CO_2 within the oceans has been assigned to a committee of scientists from ocean research institutions. The initial steps in this planning call for improving understanding by analysis and interpretation of the behavior of a number of transient tracers added by man (e.g., radionuclides) or fortuitous natural tracers transferred from air to sea and then transported within the ocean. This approach involves extensive planning for ship time, collection appara-

Table IA.5. Priority, milestones and estimated budget requirements for research on CO_2 exchange between upper and deep ocean.

Priorities:

1.	Transient tracer experiment to investigate transfer of inorganic carbon in oceans. This forms the basis for ocean transport modeling.	High
2.	Organic carbon in oceans.	Medium

Milestones and Budget:

Fiscal Year	Milestones	Budget
1980	Continue purchase and development of field equipment. Shakedown cruise in North Atlantic.	2000
1981	Conduct major sampling activity in North Atlantic.	2200
1982	Sample analysis and data interpretation. Initiation of ocean transport modeling	1500
1983	Continue data analysis and interpretation. Prepare for southern ocean cruise. Prepare draft summary report.	1500
1984	Undertake transient tracer program in southern oceans. Complete survey of state of knowledge on ocean modeling.	3000

tus, separation of the tracers from the seawater, and measurement of carbon and other constituents. Thus far, the planning has included the selection of cruise tracks in the North Atlantic Ocean for 1980 and 1981. The first of the cruises will collect data and test the instrumentation. During the second year, a major sampling effort will be undertaken in the North Atlantic Ocean. In subsequent years, cruises in the Southern Hemisphere and Pacific Oceans would follow.

The tracers to be analyzed include; ^{3}H and ^{14}C, ^{3}He (the daughter product of tritium), fluorocarbons -11 and -12, and ^{39}Ar, a cosmic-ray-produced gaseous radionuclide which has a 270-year half life. The latter isotope possess an ideal half life for studying intermediate waters of the oceans. In addition to the transient tracers, measurements of pCO_2 in air and water and alkalinity will be made as well as the usual hydrographic observations and nutrient sampling.

For selected regions of the oceans of special importance in storing or transporting carbon, such as the anticyclonic gyres, consideration is being given to the deliberate injection of a suitable tracer which would be followed for an appropriate time, to help improve understanding. A number of inert tracers are under study for this application. Accompanying the field work, a program for data analysis and synthesis will provide an ocean module for use in the carbon cycle model. The data interpretation will yield better box-type models as well as help guide development and validation of complex three-dimensional ocean transport simulations.

5.2 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 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.

It is thought that carbon is not a limiting element in marine ecosystems and only changes in the supply of nutrients such as phosphorus, nitrates and silicates could materially alter the rate at which carbon is absorbed by marine plant life and transferred to deeper waters.

If significant man-made fertilization of the ocean is taking place, and some of the increased organic matter transferred to the sediments, a 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 scale. This question should be investigated on a moderate scale to determine the order-of-magnitude of the transfer of nutrients, phosphorus, and nitrogen into the oceans by rivers and through the air and their possible role in sequestering carbon, particularly in estuaries and coastal margins.

6. Sediment Dissolution

Most current models of oceanic uptake of CO_2 from the air only consider 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 in significant amounts 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

Table IA.6. Priority, milestones and estimated budget requirements for research on CO_2 reactions with shallow and deep-water sediments.

Priorities:

Assess the role of shallow and deep water carbonate dissolution.

1.	Deep water	Low
2.	Shallow water	High

Milestones and Budget:

Fiscal Year	Milestones	Budget
1980	Hold a workshop on carbonate dissolution. Initiate a study of role of ocean biology in carbon transport.	15
1981	Literature review and initial field study of shallow water carbonate dissolution.	200
1982	Initiate field study shallow water carbonate dissolution and paper study of deep water carbonate dissolution.	200
1983	Continue study of shallow and deep water carbonate dissolution. Prepare draft summary report.	200
1984	Continue study of shallow and deep water carbonate dissolution. Complete status report on carbonate dissolution and associated processes.	200

CO_2 uptake from the atmosphere: this could be an additional sink for atmospheric CO_2. Dissolution of carbonates can be enhanced by changing water chemistry; CO_2 and other pollutants may be contributing to acidification of waters which increases dissolution.

6.1 Shallow water sediments

Although there is recent evidence that some high-magnesium calcites are dissolving in the ocean, a recent workshop concluded that this is not now a large sink for atmospheric CO_2. Dissolution of shallow water sediments could be a sink for only a few percent of the net carbon emitted to the air since the areal extent of those sediments now under attack does not appear to be large enough to be a major sink. Continued study of these sediments could be useful, however, in giving an early indication that increased dissolution is beginning to occur.

6.2 Deep water sediments

Calcite is the critical deep-sea carbonate in ocean sediment which determines the ultimate absorption of CO_2 by the ocean on 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. Roughly half of the world's total calcite lies at depths between 3 and 4 km in the Atlantic Ocean.

It is necessary to have more detailed maps of the distribution of the calcite in marine sediments than now exists. An areal distribution of calcite content of the upper few tens of centimeters of sediment should be obtained at various 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.

In addition to the distribution of the carbonates on the ocean floor, the kinetics of their dissolution requires laboratory studies of dissolution and determination of the thermodynamic solubility of the carbonate species over a range of temperatures encompassing natural conditions. Also, studies will be needed of the fluid dynamics of the benthic boundary layer, including the polar waters. This would include quantifying the effects of biological mixing of the sediments.

It is to be stressed that much of the needed research applies to both shallow-water sediments, which may be dissolving now or in the near future, and the deeper sediments, the dissolution of which will ultimately control the absorption of excess CO_2. This latter process is a slow one, having a time scale of perhaps a thousand years. First priority will go to the shallow-water sediments where the effects are likely to be of importance in the next century.

7. Other Possible Sinks

The oceans are generally thought to be the largest sink for the excess carbon not retained in the air, but it remains possible that the forests could be absorbing some of this carbon. Other possible sinks should not be neglected, however: the sum of a number of small contributions could add up to a significant quantity and some possible sinks could be larger than now estimated. We have already referred to the possibility of eutrophication of ocean margins as a possible sink. Agricultural practices, including rice paddy cultivation could contribute to storage of carbon. The additions of nitrogen and sulfur to the environment by man may be fertilizing areas other than the specific targets. Soil carbonates, particularly in arid climates, should be investigated as a possible sink of as yet undetermined magnitude.

B. Atmospheric Storage of CO_2

1. Monitoring Network

In response to recent recommendations, the world-wide CO_2 baseline monitoring network has been expanded to 19 stations at remote sites to determine the global background concentrations. Another 8 will be added very shortly. Most of these stations collect samples of air in flasks which are sent to a central laboratory for measurement. International cooperation among the participating nations is being organized through the World Meteorological Organization. The station locations have been selected for operational feasibility and avoidance of local sources of measured gasses. The world-wide network will provide global CO_2 growth rates. The observed horizontal gradients of CO_2 may (and have) suggest the places and times of sources and sinks of atmospheric CO_2. The seasonal CO_2 variations at these stations may yield clues to changes in regional photosynthesis, and the interannual changes might indicate variations in the global atmospheric circulation or sea surface temperatures. Occasional aircraft flights to give both horizontal and vertical distributions would be a useful adjunct to these single-point measurements at the surface.

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

Samples of clean air should be archived 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.

Table IB. Priority, milestones and estimated budget requirements for research on atmospheric storage of CO_2

Priorities:

1.	The world-wide network for measuring atmospheric CO_2 has been expanded. NOAA is main U.S. agency involved.	High
2.	Maintenance of standard gases available for use in measurements must continue. Some funding will be required to assure continuation of standards.	High
3.	The evaluation of gas chromatography techniques will be undertaken and if feasible, an orderly transition to this method at some of the network stations will be undertaken.	Medium

Milestones and Budget:

Fiscal Year	Milestones	Budget
1980	Expand global measuring network completed. Test of gas chromatography techniques.	100
1981	Determine feasibility of gas chromatography completed. Begin procurement and installation of instruments if practicable Continue measurements and analyses.	350
1982	Install chromatographic instruments; overlap with IR instrumentation.	350
1983	Continue measurements and analyses. Continue comparison between chromatographic and IR sensors in field locations. Prepare draft summary report.	350
1984	Continue measurements. Assess atmospheric network and its results. Complete summary of findings of atmospheric storage problem.	350

2. Standard Gases

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

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 a dilution technique capable, in principle, of the desired accuracy and has also prepared its own CO_2-in-air standards. Finally, the National Bureau of Standards (NBS) has developed gravimetric methods that may ultimately become the world standard CO_2-in-air gases. From the absolute standards, one calibrates working gas 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 non-dispersive infra-red analyzer (NDIR), future CO_2 standard gases will be CO_2-in-air: steps to accomplish the transition are underway at Scripps, National Bureau of Standards, and NOAA.

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 that might possibly be avoided by new, but untried instruments. Several shortcomings of the NDIR analyzer are: the need to dry relatively large air samples, the need for frequent intercomparison with CO_2 gas standards and the use of relatively large amounts of standard gases.

Gas chromatography is being evaluated to determine if it would provide precision as good as that now achieved by NDIR analyzers but with much reduced demands for the quantity of 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.

C. Past Records of Atmospheric CO_2

Adequate observations of the atmospheric CO_2 concentration exist only since 1958. Most of the older data, while suggesting lower values, are not precise enough to establish benchmark values. Validation of carbon cycle models would be greatly assisted by knowing atmospheric concentration--even to within a few ppm--in the latter 19th and early 20th centuries. In addition, if there have been large changes in concentration in the geologic past, knowledge of such changes, together with information on concurrent global climate, could lend support to, or suggest discrepancies in, current climate models.

Attempts are being made to deduce atmospheric concentrations within the last century by examining some of the early solar spectrographic plates. It is hoped that these can be used to infer the concentrations from the indicated absorption of sunlight by CO_2.

Table IC: Priority, milestones and estimated budget requirements for research on determining past atmospheric CO_2 concentration.

Priorities:

Determination of past (pre-1957) CO_2 concentrations on historic (past 5,000 years) time scale.	High
Geologic (> 3,000 years BP) time scale.	Low

Milestones and Budget:

Fiscal Year	Milestones	Budget
1980	Examine Smithsonian and other solar spectra for CO_2 concentration information. Examine CO_2 of ice cores. Hold workshop on geological CO_2 concentrations. Further work on oceanic techniques to reconstruct past CO_2 levels.	280
1981	Continue examination of spectra and geological records for CO_2 changes.	350
1982	Continue data analyses and interpretation of past concentration and evaluate accuracies of estimates.	350
1983	Reassess value of accepted and promising new techniques to estimate past CO_2 levels. Prepare draft summary report.	350
1984	Complete report on past CO_2 levels. Complete studies needed for final report.	350

Ice cores from the permanent continental ice sheets may contain "old air" from which CO_2 concentrations can be estimated for tens of thousands of years in the past. Possibly isotopic records in tree rings may be useful for a few thousand years.

D. Models of the Carbon Cycle

Each of the above research areas include development of model components as part of their efforts but integrating the results of these studies into a comprehensive global carbon cycle model is a final step. Its goal, of course, is the prediction of 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 found in the atmosphere, oceans and biosphere. A further discussion of these problems can be found in Bacastow and Bjorkstrom, (1980).

Progress in carbon cycle modeling will depend upon progress in determining the components of the carbon cycle, reactions to increased atmospheric CO_2, and feedback from climate changes. The models will also be useful for studies of the sensitivity of the carbon cycle (or at least its model simulation) to changes in the various components. Sensitivity studies can reveal critical parameters, areas needing more research and equally important, areas where resolving an uncertainty adds little to the ability to predict future levels of CO_2. This effort must proceed, as with all modeling efforts, in close association with data gathering and analysis.

Table ID. Priority, milestones and estimated budget requirements for research on carbon cycle modeling.

Priorities:

Development, testing and use of carbon cycle models based on new findings arising from research programs	High

Milestones and Budget:

Fiscal Year	Milestones	Budget
1980	Contract several model development efforts with scientists or organizations that have diverse interests (e.g., oceanography, biology).	300
1981	Continue to develop models. Test their output against validation data. Evaluate priorities in carbon cycle research.	400
1982	Continue model development. Engage in a national and international model comparison.	400
1983	Contract new scientists and/or organizations to develop second generation carbon models. Prepare draft summary report.	750
1984	Complete a summary position on carbon cycle models. Exercise newest models with latest energy use scenarios.	750

II. CLIMATE EFFECTS OF INCREASING CO_2

Present concentrations of CO_2 in the atmosphere, acting in combination with other absorbing gases (e.g., H_2O and O_3), play an important role in maintaining the current climate. Without CO_2 acting to absorb much of the infrared radiation emitted from the earth's surface and then re-radiating some of the energy back to the surface, surface temperatures would probably be several degrees cooler, particularly in polar regions.* The atmospheric circulation of moisture would probably also be substantially less active, and polar icecaps larger. At the same time, the stratosphere would probably be tens of degrees warmer, thereby leading to possibly altered atmospheric dynamics and probably somewhat reduced ozone concentrations.

This strong coupling between CO_2 concentrations and the prevailing climate has led to growing interest about the future climatic changes that may be induced by the projected increasing levels of CO_2. The best available, but still significantly simplified, climate modeling studies, indicate that doubling of present CO_2 concentrations would lead to an increase in mean annual Northern Hemisphere surface temperatures of 1.5 to 4.5°C (see Fig. II.1.). Studies of past interactions of CO_2 and climate and their role in the evolution of the atmosphere and possibly in past variations of glacial extent, while still somewhat speculative, form a further basis for

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* There are no models now capable of comprehensively simulating the climate assuming the complete absence of CO_2. This is because of the wide range of interacting processes, including other radiatively active gases, atmospheric chemistry, water vapor cycling and dynamics that play a role in determining the climate. The qualitative comments in the text are based on extrapolations of expected first order effects derived from model studies that incorporate CO_2 concentrations within a factor of two of present concentrations.

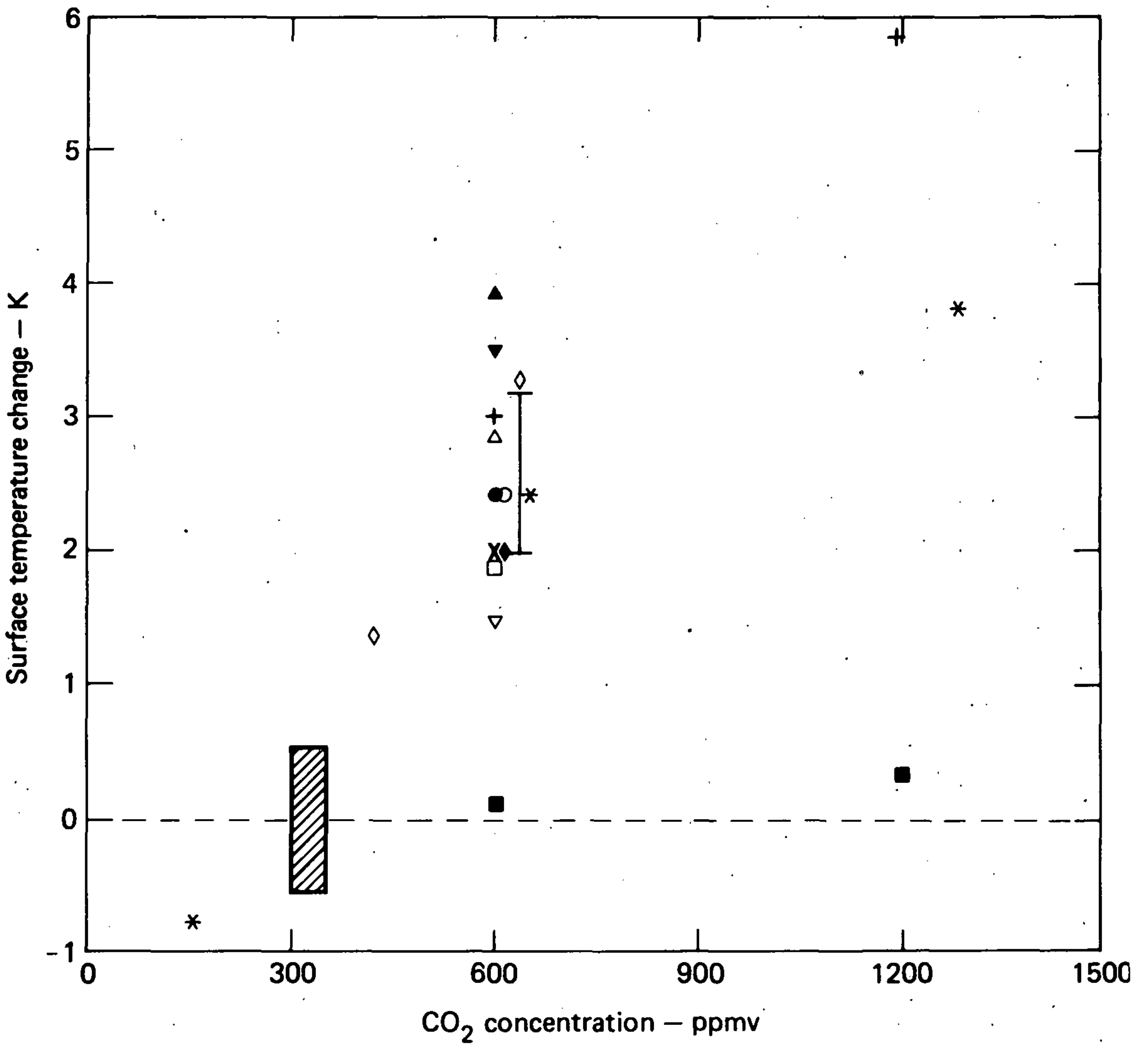

Figure II.1. Estimates of the change in surface temperature due to various changes in CO_2 concentration. Investigator: o Manabe and Wetherald (1967); △ Manabe and Wetherald (1975); □ Manabe (1971); ▽ Ramanathan (1975); ⊢⊣ Augustsson and Ramanathan (1977); x Manabe and Stouffer (1979); + Manabe and Wetherald (1980); • Wetherald and Manabe (1980); ▲ Hansen (1980); ▼ GISS (1978); ■ Gates (1980; * Potter (1978), NH value; ♦ Hunt and Wells (1979); ◊ Ramanthan et al. (1979). Manabe and Wetherald (1980) also refer to an eight times CO_2 increase that led to even further heating. Shading shows present range of natural fluctuations in climate (Mitchell, 1979) during which CO_2 concentrations have increased from about 300 to 335 ppmv. The results of Gates et al. assume no oceanic response and are therefore not included in developing the estimate of possible climatic change.

concern that the potential effects may be important. The atmosphere of Venus, with its very high temperatures, clearly indicates that high CO_2 concentrations can cause dramatic effects.

CO_2 concentrations are, however, only one factor among many that determine the overall behavior of the climate system (see Fig. II.2.). The climate system includes not only the atmosphere (and its many constituents) 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 with various driving forces in ways not now fully comprehended to comprise the climate system. The most obvious forcing functions are astronomical in origin. Of greatest importance are the changes in the distribution of solar energy caused by the daily cycle of the earth's rotation and the seasonal cycle resulting from orbit of the earth around the sun. Seemingly small variations in this orbit appear to affect climate on scales of tens of thousands of years. Variations in the sun's energy output may also affect the climate. Such variations over the last few billion years are believed to have been large, even though solar output is often referred to as "constant." Major variations in sunspot cycles over hundreds of years may also be related to fluctuations in solar energy output of a few percent, but over the last few decades, variations in solar energy appear to be below detectable limits.

The atmosphere-ocean-cryosphere-land system maintains the earth's climate by transporting heat and water vapor between equatorial and polar latitudes in order to achieve an energy balance. If the temperature gradient between the tropics and poles decreases, as current models suggest would happen if atmospheric CO_2 increases substantially, then the energy and

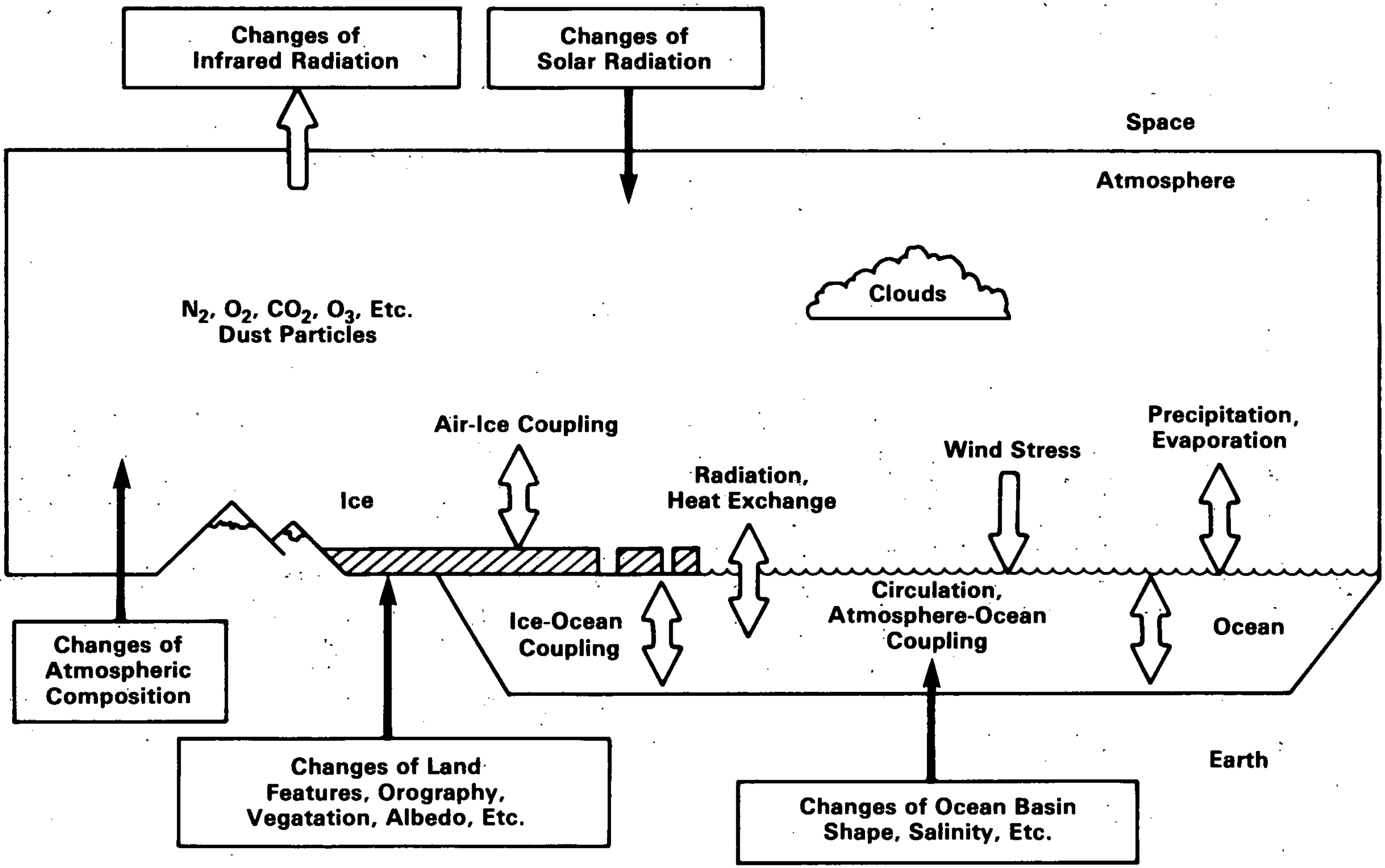

FIGURE II.2. Schematic illustration of major components of the coupled atmospheric-ocean-ice-surface climatic system. Calculation of the climatic response to increasing CO_2 concentrations requires consideration of nearly all of these factors (Ref. NAS, 1975). The thin arrows refer to "extermal" processes, the broad arrows refer to processes "internal" to the climate system.

water vapor exchange would also be expected to change and some new circulation patterns and precipitation regimes could evolve. These new circulation patterns could well lead to substantially different regional climates (i.e., temperature, precipitation, winds, etc.). Due to the complexity of the climate system, these regional changes could be greater than, and in some cases possibly opposite in sign to, changes in the global average.

Observations and analyses of past conditions show that climate is variable on a wide range of time and space scales. The causes of this natural variability are little understood, although they have affected man's activities significantly throughout history. Even without man's intervention, these natural variations will continue. When man's impact will be noticeable amongst the natural fluctuations and cycles, and whether the climatic effects of increasing CO_2 concentrations will add to or counteract the as yet unforeseeable natural changes (or even the effects from other man-made factors) are complex questions, but hopefully not unanswerable.

To determine the climate response to increased CO_2, the climate research elements of the plan will be focused on answering the following major questions:

- What will be the seasonally-dependent regional and global climatic changes induced by projected changes in atmospheric CO_2 concentration?
- How rapidly will the climatic changes be taking place and to what extent will the projected changes depend on the time-dependent characteristics of the climate and the rate of increase of CO_2?
- To what extent are the projected changes dependent on other climatically-related events and activities of man and nature?

The first question is intended to focus on determining the quasi-equilibrium* climatic change to which society becomes committed by increasing the atmospheric CO_2 concentration. Because the temporal response characteristics of the atmosphere, oceans, ice, and land surfaces are quite different, however, the actual climatic changes that occur will probably be delayed and might even be different than the quasi-equilibrium projections. The second question is intended to address these issues so that assessment studies and the search for evidence of climatic change can consider the time-varying nature of the response, including the dependence on varying rates of increase of CO_2. The projected change in CO_2 concentration is, of course, only one of many possible influences on climate. In developing estimates of the limits of possible climatic changes, the DOE CO_2 program must consider, at least indirectly, the possible climate effects of such other influences as volcanoes, chlorofluorocarbons, other combustion emissions, and surface albedo change, so that a proper context for of the CO_2-induced climatic changes can be provided.

To address the three key questions, a four part research program (Fig. II.3.) is being developed that draws on efforts to understand both the present climate and past climate changes. The program stresses those increments of a total climate research program that are most directed toward resolving the uncertainties in estimating the effects of increasing CO_2 on climate. Initial efforts to develop improved understanding and analytical techniques are followed by application and the seeking of confirmation of estimates in the real world. The basic components the research program will include:

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* Because the real climate is never truly in equilibrium, and because the CO_2 concentration will be constantly changing, an estimate of the quasi-equilibrium change may be most appropriate for purposes of comparison and evaluation.

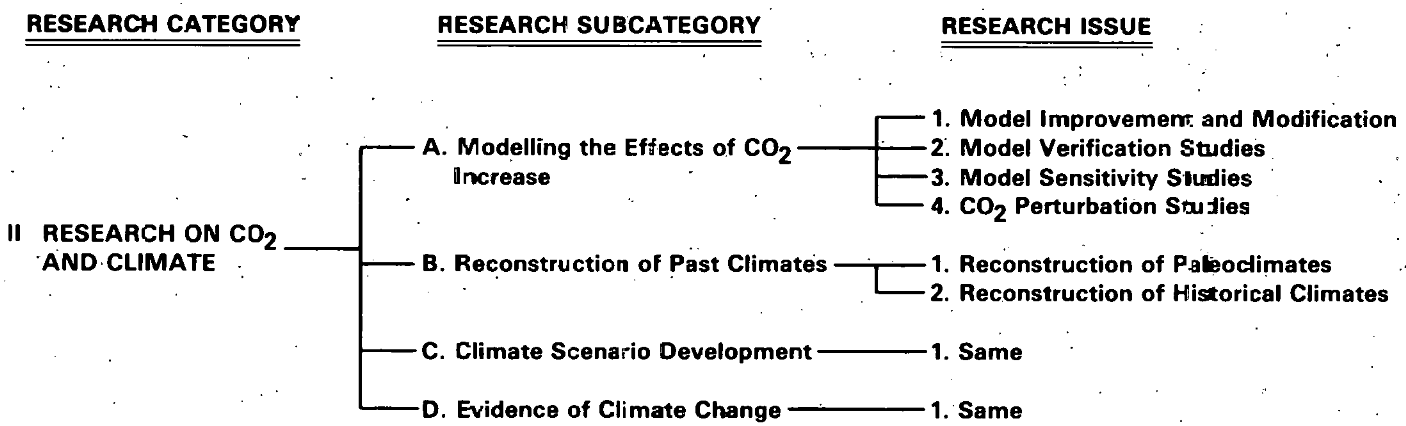

FIGURE II.3. Principal Research Issues for Estimating the Climate Response to CO_2

- Developing improved, verified models for use in estimating limits on the climatic effects of increasing CO_2 concentrations;
- Searching historic and paleoclimatic records for evidence of different climates (particularly those warmer than the present) that can be used to study the mechanisms of climate change, to determine the ranges of past climate variations, and to develop analogs of possible CO_2-induced warmer (and warming) climates;
- Using model-derived expectations of climate change, evidence of past climate change, and our experience with the present climate to develop scenarios that encompass plausible upper and lower limits of the possible CO_2-induced future climate conditions. So that adequate ecological, social, and economic analyses can be made, the scenarios must estimate changes in such parameters as regional and seasonal variations of temperature and moisture in agricultural and watershed areas; extent of sea-ice, ice shelves, and mountain snow; and ocean currents and temperatures in areas of substantial oceanic productivity.
- Evaluating and analyzing present data in search of evidence that expected CO_2-induced climate changes have in fact occurred.

Table II.1. summarizes the priorities, and provides budget estimates for scientific planning. The priorities and recommended budget levels implicitly include estimates of the value and timeliness of the approach, the potential for progress, the level of activity in these areas outside of DOE, and the overall importance of the particular activity in the CO_2 program as a whole. It is because of the relatively large uncertainties in climatic response that this last factor causes climate efforts to be almost uniformly

TABLE II.1. Summary Budget and Priority Recommendations for CO_2 Climate Research

Research Subcategory	Research Issue	Priority	Recommended Budget FY-80	FY-81	FY-82	FY-83	FY-84
Climate Modeling	Development & Modification Verification Studies Sensitivity Studies Perturbation Studies	Very High	750	1500	1700	1700	1900
Past Climate	Paleo-climate	High	200	300	400	500	500
	Historic Climate	High	100	150	200	300	350
Scenario Development		Medium to High	0	200	300	400	400
Evidence of Change		Medium to High	0	50	100	100	150
Total			1050	2200	2700	3200	3300

so highly rated. The budget will support pursuit of the principal research thrusts for estimating the effects of increasing CO_2 concentrations on climate, including:

- Improve model treatment and understanding of the feedbacks present in the coupled ocean-atmosphere-cryosphere-land surface-biota system.
- Conduct seasonally-varying simulations of the effect of enhanced CO_2 on the climate with a variety of models, particularly general circulation models including realistic oceans and geography, so as to place limits on expected perturbations.
- Compare model results, identifying the processes contributing to discrepancies both among models and between models and the climate system.
- Search and document historic and paleoclimatic records for periods of climate change, particularly for warm climate conditions and warming events, to use as analogs for predicting likely changes in climate for various regions and to determine the range of past climate variations.

Coupled with the principal thrusts, additional support will be needed to:

- Improve model parameterizations of such processes as clouds, oceans, land surface and the hydrologic cycle and understand better the role of these processes in determining model sensitivities and the climatic response to increasing concentrations of CO_2.
- Extend and expand model verification studies and sensitivity analyses to include comparison of global circulation model calculations of warm climate analogs with the historic records.

- Develop techniques and approaches to speed early identification of a CO_2-induced climatic response.

At present, plans are being formulated for intensified programs and activities, both nationally and internationally, to improve the understanding of the whole climate system and its variations (e.g., refer to the National Climate Program Plan). Study of the CO_2-climate problem must be (and is being) integrated into these emerging international programs. The advances of these programs that lead to better understanding of the climate's "unperturbed" state will help build confidence in predictions of the CO_2-perturbed climate.

Although this research program attempts to place the projected climatic changes in perspective of past climate changes, this research program does not attempt to evaluate the environmental impacts or the economic significance of these climatic changes; that part of the research plan appears in a later part of this Comprehensive Plan.

A. Modeling the Effects of CO_2 Increases

There has never been a climatic situation exactly like that envisioned from increasing CO_2 concentrations. Therefore, we cannot simply look back to past conditions to predict climate conditions for the future. Numerical models will have to be the primary tools used to make climatic projections, although our experiences of climates past must temper our evaluation of model projections.

To generate confidence, models must represent all of the relevant aspects of the chemistry and physics of the atmosphere, hydrosphere, cryosphere and biosphere, and be verified against a wide variety of past climate change scenarios. Because the models depend on the extent of our understanding of the many processes that are involved--particularly of the numerous complex and subtle feedback mechanisms--there is great need for fundamental improvements in our perception of how the climate system functions. Especially because the projected climate changes are unprecedented in mankind's documented climatic experience (i.e., in at least the last 100,000 years), there is the possibility that we are overlooking important mechanisms or improperly representing processes as climate conditions evolve beyond the range of validity of various parameterizations.

In addition to projections of the actual climatic changes, the crucial questions that must be addressed as part of the climate modeling element of this research plan include:

- What CO_2-related processes are not now adequately treated in numerical models?
- Can improved models adequately represent the present climate?
- Are improved models consistent with available information on past climatic changes and conditions?
- Can available and planned climate models provide the information needed to estimate the climatic effects of increasing CO_2?

Each of these questions will be the focus of research within the climate modeling subcategory. The use of the word adequately is intended to convey the need to develop a sense of reasonable confidence rather than of certainty, in recognition of the many causes of uncertainty, some inherent. As indicated by the first question, perhaps of most immediate concern with present projections are the many simplifications made in most of the numerical models being used to project future climate. Present models, for example, are only beginning to treat realistic topography, land-sea distributions and seasonal variations, and still treat only poorly land surface and cryospheric processes, ocean heat capacity and transport, and clouds. Many of these problems can be corrected or, at least, their climatic effects can be much better represented. Although it is not likely that we will have completely satisfactory climate system parameterizations during the next five years due to a combination of limitations including computer capacity, diagnostic capabilities, and lack of a fundamental understanding of many of the components of the climate system, there should be a sufficiently adequate representation of the system to allow reasonable limits to be placed on the effects of increasing carbon dioxide.

Because of the large number of processes that make up the climate system, a wide range of analytic and numerical models have been developed to represent it. This breadth of approach, ranging from relatively simple one-dimensional models to comprehensive three-dimensional ocean-atmosphere models, offers some assurance that the full range of important response mechanisms are at least being considered since in each model efforts are made to incorporate many of the processes having the temporal and spatial response characteristics appropriate to the issue at hand. The temporal and spatial aspects of the CO_2 problem, however, do require treatment of more mechanisms than are normally required in just representing the present climate.

Much of the work that needs to be done involves improvements in the General Circulation Models (GCM), because these comprehensive, time dependent, three-dimensional simulations offer the best hopes for predicting regional climate changes. There is an important, complementary role, however, to be played by less elaborate, and hence less expensive and less time consuming, Statistical Dynamic Models (SDM), especially if model parameterizations are coordinated between the various types of models. Such models are usually of only one or two dimensions, and treat only in an empirical fashion at least some important elements of the atmospheric physics. Some of these simpler models can be used for investigations of specific physical processes (e.g., cryospheric processes), others will be useful for studies of the sensitivity of climate systems to variation of certain variables. In addition, there may be more appropriate simplifications than are now in use, approaches that may be even better suited to the CO_2-climate problem (e.g., a three-dimensional atmosphere-ocean model with statistical dynamics to allow longer time steps). Such models should be used in concert with the GCMs by, for example, examining questions of long term variations that are very difficult to perform with GCMs and by developing boundary conditions (e.g., evolution of glacial ice) for use in GCM calculations. Simplified models can also be used to determine effects of other radiatively active gases and particles that man releases to the air and that 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 being planned by a number of groups with the necessary competence and computer facilities, 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. Parallel work by different groups is to be encouraged since each model includes different characteristics and approaches. Contact between the groups should be further encouraged. Coincidence of results among the groups will lend some additional credence to the forecasts, although all model results may also suffer from similar shortcomings. Any divergence of results must be examined very carefully to determine whether the differences represent model deficiencies or a lack of knowledge of the climate system.

Finally, it should be emphasized 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 functions produces a unique climate) or whether it is determined by random interaction of the various internal processes. Fundamental insights into the dynamics of the natural climate system are a prerequisite to more accurate determination of the response of the climate to increased carbon dioxide.

The five-year program described in the following subsections will focus on the following research tasks:

(1) Develop, modify, improve, and test model parameterizations of important processes, so that plausible maximum and minimum feedbacks from these processes can be provided.

(2) Extend model verification studies to include evaluation of the capability of models to represent seasonal variations and past times when climate was different than the present.

(3) Perform systematic model sensitivity studies to evaluate the effects of uncertainties in our understanding of the climate system and to estimate the size of the feedbacks of various processes and mechanisms.

(4) Conduct more sophisticated CO_2 perturbation studies to determine limits of regional effects, time lags, and environmental interactions (e.g., changes in the cryosphere, hydrosphere and biosphere).

Based on consideration of the factors contributing to uncertainty, highest priority should be given to the development and intercomparison of coupled ocean-atmosphere models (both GCMs and SDMs), their verification against observed seasonal variations and major climatic changes of the past, and finally their use in establishing regional effects of CO_2 perturbations. Second priority should be given to coupling these models to the cryosphere so that effects in polar regions can be studied. Also of high priority are consideration of the treatment of clouds, verification against past regional climatic conditions, and model sensivitivy studies as a means of establishing estimates of uncertainty. Details are discussed in the following subsections.

1. Model Improvement and Modification

Model development, improvement, modification, and testing is a continuing and on-going process among the many groups developing numerical models. To accelerate an improved treatment of the potential climatic effects of increasing CO_2 concentrations, however, requires improvement and testing of particular aspects of these models that may not now be of critical importance in studying non-CO_2 issues. A hierarchy of models will continue to be needed to gain overall insight because of the great range of processes involved. Increased emphasis will be placed on use of GCMs to investigate regional effects and on improving particular parameterizations in SDMs so that results from the two types of models can be better intercompared. In addition, some new models may be needed that focus on particularly important processes (e.g., vertical exchange processes in the oceans, polar climate).

Although the direct radiative effects of CO_2 induce a relatively rapid atmospheric response (e.g., days), the indirectly induced climate effects on the oceans, ice, and land surfaces have a much longer time constant (up to

Table IIA.1. Priority, milestones and estimated budget requirements for research on climate model improvement and modification.

Priorities:

Improve treatment of the oceans, cryosphere, and clouds.	Very High
Improve treatment of radiation, composition, boundary layer physics, and the land surface.	High

Milestones and Budget:

Fiscal Year	Milestones	Budget
1980	Initial construction of coupled ocean-atmosphere circulation models and seasonally varying simplified models.	(Refer to Table II.1. for budget data.)
1981	Improve treatment of cryosphere in climate models; intercompare cloud parameterizations; continue work on treatment of oceans.	
1982	Continue improvement in treatment of radiation, composition, boundary layer, land surface and ocean prescriptions.	
1983	Continue improvements. Prepare draft summary report.	
1984	Continue improvements.	

hundreds of years). Since changes in these conditions in turn can further affect the climate, climate models for CO_2 studies must properly treat a very wide range of processes. The major improvements needed in models are now generally recognized to involve treatment of the oceans, cryosphere, clouds, radiation, composition, boundary layer physics, and the land surface and biota. One of the priorities of this program will be to determine which of these areas are most important to placing limits on the climatic effects of enhanced CO_2, and then encouraging improvements in the model treatment of those areas.

1.1 Oceans

Oceans strongly affect the atmospheric climate by transporting heat poleward, storing heat as the seasons change, and acting as local sources or sinks of water vapor and heat. Many of the present models, however, treat oceans very simply; for example, as being at constant temperature or as having zero heat capacity. The critical importance of proper representation of the oceans is clearly evident in Fig. II.1., which shows that model simulations in which ocean temperatures are not allowed to change from present values (Gates et al. 1980) give substantially lower atmospheric temperature increases than model simulations that permit instantaneous local ocean temperature adjustment.

Since land-ocean temperature differences play an important role in determining actual weather patterns, which in turn generate the wind stresses that help drive the ocean currents, improved treatment of the oceans is of very high priority, both for climate and effects studies. While it may well be several years before a sophisticated ocean model including ocean currents and heat transport can be properly coupled to an atmospheric model, it is possible that simpler approaches will yield significantly improved climate predictions. For example, an ocean model whose mixed-layer depth and temperature are brought into thermal equilibrium with warmer atmosphere would be such a useful early candidate. Consideration can also be taken of the fact that the response time for adjustment of the entire ocean to an atmospheric change is on the order of centuries, so that ocean models without all of the details of the deep ocean circulation may be satisfactory.

Highest priority must be given to extending the domains of climate models to include treatment of, at the least, the ocean's mixed layer. More extensive treatment of upwelling and deep mixing, changes in mixed layer depth, and processes involving intermediate ocean layers must also be pursued.

1.2 Cryosphere

Global snow and ice play many important roles in influencing the climate. Their high albedo reflects solar radiation that otherwise would warm the earth, thereby allowing further growth in ice extent (the so-called ice-albedo feedback). Sea ice limits evaporation and release of heat from ocean areas and, by its presence protects large areas of ice shelves and glacial ice grounded below sea level. Land ice stores water that would otherwise inundate coastal lands. Of the five regimes involving 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 so that existing models can be better verified and future effects better estimated.

1.3 Clouds

Clouds reflect back to space about 15-25% of the incoming solar radiation (thereby tending to cool the surface), but they also tend to restrict the earth's emission of infrared radiation (thereby tending to warm the surface by a similar amount). In addition, of course, clouds are involved in the hydrologic cycle in the atmosphere, although changes in cloudiness are not easily related to changes in precipitation. If global cloudiness should change (either cloud amount, height or latitudinal distribution) in response to CO_2-induced warming and circulation changes, an important radiative feedback mechanism could exist that is now handled in models only crudely, in large part because of a lack of fundamental understanding. Although some recent work suggests that the radiative effects of clouds may not be as important as previously thought on a global basis (because solar and longwave influences tend to compensate), more thorough analysis of surface and satellite data on cloud type, amount, and height and more satisfactory treatment of clouds in models are needed to assess latitudinal, seasonal, and regional effects, particularly in polar areas. Model studies using various approaches to representation of clouds may also be useful in placing limits on the role of this feedback mechanism.

1.4 Radiation

Radiative processes are the primary influences controlling global temperatures. Although the radiative properties of carbon dioxide are reasonably well known, there remain some possible problems with the radiative properties of a mixture of gases with overlapping absorption bands. Water vapor is the prime example of a gas with such overlapping absorption spectra. Absorption by the hot bands of water vapor, in particular, will become of increasing importance as temperature and water vapor concentrations rise. Measurements of atmospheric infrared fluxes show enhanced emission that has been attributed to a water dimer. Other gases, particularly man-introduced gases such as the florocarbons, 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.

1.5 Atmospheric Composition

As energy use increases and the climate warms, other gases may also become of more importance in the radiation calculations than at present. Carbon monoxide, nitric oxide, and methane--some of which are emitted along with the CO_2 emissions as carbon fuels are combusted--can alter atmospheric chemistry and thereby influence the radiative balance. Atmospheric aerosols, both liquid and solid, are also influenced by man's activities, and projections of future conditions may indicate increased importance of such materials in determining atmospheric temperatures. The altered temperatures could further alter the atmosphere's composition (e.g., stratospheric ozone will increase as stratospheric temperatures cool). The different radiative spectral pattern could in turn affect other parameters (e.g., albedo).

No specific recommendations for research on these questions are suggested now, but the need for studies of atmospheric chemistry and the radiative properties of aerosols and gas mixtures will be further considered.

1.6 Boundary layer physics

The parameterizations of clouds and of the boundary layer form a coupled problem. Stratus clouds are formed in the boundary layer. Cumulus clouds are forced by heat and water vapor transport through the boundary layer. More realistic parameterizations of this coupled system have taken 5 to 10 years to develop and are just now being tested in GCMs. The success of these parameterizations could greatly improve our ability to simulate climate change.

1.7 Land surface and biota

Although the ocean largely controls the global atmospheric response, it is on the land and through the biota where the influences of climate change will be primarily felt. The accuracy of model simulations of regional climate changes will be determined largely by the fidelity with which the models translate the atmospheric changes into changes in surface conditions, a translation process involving important, but poorly understood, feedback mechanisms. To improve the climate simulations, models will have to better represent evaporation processes, runoff, albedo, roughness, soil temperature and moisture, frost, and the biota's role in influencing these factors. Not only do these factors control the regional climatic response, but they are also the crucial interface with the many effects studies that are being undertaken as part of the Comprehensive CO_2 Program. Improvement of model representations of surface processes will be encouraged as part of this program, with priorities for efforts within this area established in conjunction with the needs of the researchers conducting effects studies.

2. Model Verification Studies

Once models are constructed, it is essential that their results be compared to the observed climate. While this may seem an obvious and straightforward step in evaluating the uncertainty of models, it is actually a very complex process. Comprehensive ocean-atmosphere general circulation models attempt to represent all of the important complexities of the real system. Comparison with data then becomes extremely difficult and isolation of the causes of differences between model results and the real world is very time-consuming. Verification of the behavior of individual processes provides some simplification, but theoretical limitations and limited model resolution seriously complicate intercomparison of models with the real world. Increasing the coordination of GCM verification, however, with that for simpler models may offer opportunities for fuller testing of parameteriza-

Table IIA.2. Priority, milestones and estimated budget requirements for research on climate model verification

Priorities:

Verification against seasonal cycle.	Very High
Verification against past climate variations, changes, and conditions.	High

Milestones and Budget:

Fiscal Year	Milestones	Budget
1980	Continue verification studies against equilibrium climatic conditions (e.g., fixed sea surface temperature, etc.)	(Refer to Table II.1. for budget data.)
1981-82	Verification of model representations of seasonal cycle, including verification of coupled ocean-atmosphere models.	
1983	Prepare draft summary report.	
1984	Continue verification studies.	

tions and the role of particular processes in determining the model climate.

Progress over the last twenty years has been slow but steady. Prospects for the next decade appear somewhat more hopeful, however, due to increased computer capacity, improved analysis techniques, expanded model domains, the increased availability of past climatic data, and the vast increase in present data made possible with new satellite capabilities.

Past verification studies have often considered only annual average or equilibrium seasonal conditions that do not test the model's responsiveness to changing conditions. Major improvement in our confidence in models and in our understanding of their deficiencies can be expected to follow from a rigorous verification of model simulations of:

- the annual cycle of the seasons,
- the relative freqeuncy and seasonal variation of different weather patterns,
- the diurnal cycle,
- interannual fluctuations,
- climatic variations during the last hundred years; and
- a variety of glacial and interglacial climates and climatic changes on scales from hundreds to hundreds of thousands of years.

Of great importance will be analysis of how well models are representing those processes that tend to amplify the direct radiative effects of increasing CO_2 concentrations, particularly the relative humidity, water vapor, snow and ice cover, sea surface temperature, storm tracks, frequency of weather types, internal variability, and geographical pattern of seasonal variations. The past hundred years, with its variation in volcanic aerosol loading, umbra/penumbra ratios, and sunspots, among other changes, offers wide possibilities for evaluating the validity of model responsiveness on time scales from years to decades. Modeling of the glacial and interglacial climate regime may also offer the opportunity to identify key sorts of paleoclimatic information that may help in identification of mechanisms that cause climatic changes. Increased effort can also be expected on comparing model results for particular continental regions with extended histories for those areas.

Improvements in treatment of processes such as air-sea interaction and annual snow cover will allow more realistic model responses for the various verification periods, so that the focus can move from verification of mean quantities to comparison of moments and variations. Diagnostic techniques being developed for simple models will be extended to the more complex models (and vice-versa).

Within the next five years, we should have available much improved models that have been better tested against a wider variety of climatic regimes--models in which we can have greatly improved confidence.

3. Model Sensitivity Studies

Sensitivity studies are a second important aspect of the testing process required to determine the validity of numerical models. It is such studies that help us to understand what mechanisms control and influence the climatic response to pertubations. Because no model can include all of the relevant mechanisms, sensitivity studies can be used to determine which feedbacks are important and which can be largely ignored. Common sensitivity studies (e.g., variation of the solar constant) using different numerical models and different types of models can help clarify differences in results between models. Once such comparisons are understood, the various models can be used to study the many different problems in a coordinated way.

Table IIA.3. Priority, milestones and estimated budget requirements for research on climate model sensitivity studies.

Priority:

Determintion of the sensitivity of numerical models to changes in various parameters influencing the climate will help understand the factors controlling the climate.	High

Milestones and Budget:

Fiscal Year	Milestones	Budget
1980	Initiation of studies to understand the role of the parameterization of the ocean in influencing climatic sensitivity.	(Refer to Table II.1. for budget data,)
1981-83	Further investigations of model sensitivity to variations in solar input, land surface processes, snow and ice cover, and ocean circulation. Prepare draft summary report.	

A wide range of such studies is possible. Each can play a role in helping understand how particular aspects of the models are working. The most common and most important studies will involve:

- variation of the solar constant;
- variations in cloud amount, height, albedo, and latitudinal distribution;
- ice-albedo feedback (including both sea ice and land snow and ice variations);
- sea surface temperature change;
- land albedo and soil moisture changes;
- ocean circulation characteristics; and
- stratospheric aerosol loading.

Such testing should permit analyses that will take into account the role of possible biospheric feedback mechanisms (e.g., changes in vegetation patterns), changes in solar input related to sunspots or volcanic eruptions, climatic effects of ocean current changes that we may not be able to predict directly, and so forth.

These studies will also allow partial model verification against a number of specific, often short-term phenomena; as for example, especially cold years believed to have followed major volcanic eruptions. For some of these studies there is evidence from past climate studies indicating the possible range of the expected response. Our studies will provide an indication of the time constants or spatial extent of the possible changes. Still others will provide information on where evidence of change will first occur. And all will help in understanding how the differences in results from different models can be reconciled.

While advances in climate modeling will require that a wide variety of sensitivity studies be done, DOE will be working with other agencies supporting climate research to coordinate these efforts so that those most important to the CO_2 studies are accomplished.

4. CO_2 Perturbations Studies

Only within the last year have CO_2 perturbation studies (e.g. Manabe and Wetherald, 1980) begun to move beyond relatively crude simulations of annual average changes with idealized topographic and surface conditions. While these simulations tend to reinforce earlier work that Northern Hemisphere annual-average surface temperatures are likely to increase 1.5 to 3.0°C, or perhaps more, for a doubling of CO_2, they are only beginning to offer additional insight into seasonal variations, changes in precipitation patterns, and the probablility of melting of polar sea ice.

There remains much to be done, however, and the next several years offer the prospect for significant progress. Assuming that a projection of future CO_2 concentrations is independently specified, studies are needed that consider how the increased CO_2 concentrations will perturb the climate with particular attention being paid to the following questions:

- What is the projected, quasi-equilibrium climatic change for some specified future CO_2 concentration (e.g., a doubling)? The projected changes should be specified in terms of seasonally and latitudinally dependent changes in temperature and precipitation.
- How will oceans act to modulate or alter the projected quasi-equilbrium climatic change? Will delay of the projected equilibrium response change the equilibrium response?

Table IIA.4. Priority, milestones and estimated budget requirements for research on CO_2 perturbation studies

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Priority:

Perturbation of the atmospheric condition of CO_2 in time dependent scenarios.	Very High

Milestones and Budget:

Fiscal Year	Milestones	Budget
1980	Preliminary estimates of regional effects from three-dimensional model(s).	(Refer to Table II.1. for budget data.)
1981-82	Preliminary results from coupled ocean-atmosphere models.	
1983	Results from comprehensive climate models, including further estimates of regional effects. Prepare draft summary report.	
1984	Systematic estimates of the limits of climatic effects on a regional and seasonal basis.	

- What regional changes in climate and climatic variability will be induced by the projected global changes? Particular attention should be paid to such aspects as changes in frequency of weather patterns, frost, diurnal pattern of the variation, land-ocean differences, and influences on agricultural and water resource regions.
- What climatic changes will be induced in polar regions and how do these relate to changes in land and sea ice and snow cover?
- What changes in oceanic circulation and air-sea exchange result from the perturbed climatic conditions, and how do these changes in turn affect the climate and sea ice?
- To what extent are these answers dependent on the rate of change of carbon dioxide concentration?
- What is the degree of uncertainty in these answers, and to what extent are they dependent on the type of model and the treatment of particular processes?

Studies are needed that consider not just the changes when a new equilibrium climate is established, but also what changes occur as CO_2 concentrations are increasing. Because the natural climate is not constant, the effect of fluctuations such as those that have occurred in the past must be considered to determine whether amplification or cancellation of effects is possible when fluctuations occur in the future.

Together with analysis of data and characteristics of the present climate, a modeling approach including both GCMs and SDMs offer the potential for addressing all of these questions, at least in a preliminary way, during the next five years.

B. Reconstruction of Past Climates

If our understanding of the atmosphere-hydrosphere-cryosphere-biosphere system were complete and if model results compared well with data on past climates so that very high confidence could now be placed in model predictions, then we could rely solely on numerical models to simulate the climatic effects of increasing CO_2. Unfortunately, we do not understand any of the climate system sufficiently accurately to be able to assure that our models will yield the proper magnitude, perhaps even the sign, of all of the individual climatic responses. Thus, although a model may indicate a 3°K average annual warming for the Northern Hemisphere, regional effects may be larger, smaller, or of opposite sign; precipitation at a particular location may increase, decrease, or change its seasonal distribution; and ocean fishing conditions may improve or deteriorate.

Therefore to supplement model results to gain basic information about the physics of climate (e.g., interactions, oceanic time lags, ice sheets, biota, etc.), and to provide additional climatic regimes against which model results can be evaluated, DOE's Carbon Dioxide Program will support research on reconstruction and diagnosis of past climates. The research will seek to gain information from studies of a variety of past climates and climatic changes and trends and patterns in historic data. These efforts should be particularly helpful for projecting regional temperature changes and changes in related climatic parameters such as precipitation. Because recent model studies have indicated that the simulated climate responds similarly to various warming influences (e.g., increased CO_2, increased solar radiation), it may be appropriate to assume that understanding gained from studies of past warm climates and warming events (for which we do not know the cause) may be useful in projecting ahead to the future warm climate conditions that

CO_2 is expected to induce. We may also gain insight on the responsiveness of the climate to changes in boundary conditions, experience that may be useful in testing numerical models. However, current knowledge of the paleoclimatic record remains very limited and the need for information to use in testing numerical models is great, so that it would be premature to restrict the scope of paleoclimatic research to particular "analogs" or time intervals.

It is interesting that in attempting to reconstruct past climates, we are actually doing so by looking at the environmental and ecological effects of past climates. Thus, this aspect of the climate reserch effort is tied very closely to effects studies, and may offer very useful insights on the analysis of model results in terms of ecological impacts.

Just as with model results, it will be important that great care be taken in paleo-climate analysis. Complicating factors include limitations on temporal and spatial coverage and resolution, effects of potential competing influences (e.g., different solar orbital effects, sunspots, volcanic conditions, etc.), and identification of changes in variability as opposed to changes in the mean climate. Moreover, we do not yet know the causes of past changes and so may not appreciate fully the differences that may be induced when CO_2 is the perturbing factor. If at all possible, therefore, we should seek to gain understanding of the causes of past changes--not just of the changes themselves. Study of cooler periods than present will also be helpful in this quest.

Such paleoclimatic data as pollen and glaciologic records and ocean sediment cores have shown that the warmest part of the hypsithermal--a period from about 5000 to 7000 years ago--was considerably warmer (1° to 2°K) than present in the North Atlantic basin and neighboring continents. Observational records have also shown that the early to middle decades of this century were comparatively warm in the Northern Hemisphere. These two periods appear to offer the best opportunity for the expanded analyses that are necessary to better document the global effect and regional variations to be expected from a warming. The variety of other major climate changes over the last 20-30,000 years, including the most recent glacial maximum (18000 YBP) transitions to maximum interglacial (5-7000 YBP*) and subsequent changes to the present, can also be expected to offer insight.

1. Reconstruction of Paleo-Climates

The global climate is believed to have been warmer than present for most of the earth's existence, but colder than present during most of the past 2 million years. The most recent warm periods were during the last interglacial (the Eemian-Sangamon some 120,000 years ago) and during the maximum of the current interglacial, sometimes referred to as the hypsithermal (5000 to 7000 years ago). There is substantial interest in the former period as a means for investigating the onset of a major glacial period, particularly because sea level was 5-6m higher than present, indicating that one or more of the polar ice sheets must have been smaller. Data on the period, however, may be too sparse to provide estimates of regional paleo-climate patterns.

Data are even more difficult to reconstruct for the much warmer Tertiary period, the time more than 20 million YBP, before the Antarctic continent acquired its ice sheets. The period between about 20 million YBP and 5 million YBP may be of particular interest, however, because there was a marked asymmetry in the hemispheric climates due to the fact that the southern polar regions were glaciated and the northern polar regions were not

* YBP means Years Before Present, where the present is set as 1950.

Table IIB.1. Priority, milestones and estimated budget requirements for research on reconstruction of paleo-climates

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Priorities:

Reconstruction of paleoclimates of the last 30,000 years with particular emphasis on aspects that will provide insight into the climatic changes that may be induced by increasing CO_2.	High

Milestones and Budget:

Fiscal Year	Milestones	Budget
1980	Expand area studies of the hypsithermal and other climates and climate changes of the past 20-30,000 years, using pollen, sediment, and glaciological features as indicators of past environmental conditions.	200
1981	Survey data from hypsithermal period to find regions where early indications of warming conditions appeared.	300
1982	Continue studies, looking at regional changes that occur in major climatic transitions, with increased emphasis on the Pacific basin and Asian mainland.	400
1983	Integrate knowledge about climatic behavior gained from studies of past climates and develop composite estimates concerning characteristics of future warm climates. Prepare draft summary report.	500
1984	Continue studies and participate in development of integrated CO_2 scenario.	500

(Flohn, 1979). Such a situation could recur with a CO_2 warming, and its global circulation patterns might be quite different than the present.

The maximum in the recent interglacial, or hypsithermal period, may offer substantial information. Analysis of sediment cores should provide extensive information on ocean surface temperatures, patterns of major currents, sea ice extent, and glacial volume. Glaciologic investigations can provide information on annual variations, if enough information is available on present hydrologic conditions. Kellogg (1977) has summarized much of the available data on surface conditions. Efforts to fill gaps in the records, particularly in the Pacific basin and the Asian mainland, and to provide better temporal resolution using land and marine data should be able to improve understanding substantially during the next decade.

The program will work with other government agencies to encourage research into those aspects of the climate of these periods that may bear on the CO_2 issue. Particular effort will focus on assembly and analysis of existing data, investigation of the mechanisms governing warm and warming periods, evaluation of the time constants controlling climatic response, and preparation of data bases for model verification.

2. Reconstruction of Historic Climates

Historic data, much of it indirect, indicate that a several hundred year period about a thousand years ago was slightly warmer than the present, again particularly in the Atlantic basin. Since that time there have been several periods lasting a few decades that have been warm, but in general the climate has been somewhat cooler (up to perhaps 1°K) than present. While the changes are therefore somewhat smaller than between the present and the warmest times of the hypsithermal, there is the opportunity to

Table IIB.2. Priority, milestones and estimated budget requirements for research on reconstruction of historic climates

Priorities:

Analysis of climates of the last thousand years, particularly the last hundred years, to improve understanding of the global and regional nature of climate and its fluctuations and variability	High
Historical climate changes related to water and agricultural resources.	High
Historical climate changes of polar regions.	High

Milestones and Budget:

Fiscal Year	Milestones	Budget
1980	Expand areal studies of the hypsithermal and other climates and climate changes of the past 20-30,000 years, using pollen, sediment, and glaciological features as indicators of past environmental conditions.	100
1981	Survey data from hypsithermal period to find regions where early indications of warming conditions appeared.	150
1982	Continue study, looking at regional changes that occur in major climatic transitions, with increased emphasis on the Pacific basin and Asian mainland.	200
1983	Integrate knowledge about climatic behavior gained from studies of past climates and develop composite estimates concerning characteristics of future warm climates. Prepare draft summary report.	300
1984	Continue studies and participate in development of integrated CO_2 scenario.	350

estimate the potential climatic effects of increasing CO_2 by contrasting warmer and cooler periods using considerably more accurate data and over a time scale better matched to the CO_2 issue.

A second historic warm period occurred in the first few decades of this century, when temperatures were perhaps a few tenths of a degree warmer than at present. Analysis of the regional nature of the changes, which resulted in drier (and in some cases, dust-bowl) conditions in the U.S. plains, may provide important insight into possible patterns of climatic response and changes in frequency of occurrence of various weather patterns. Efforts can also be made to develop climatic composites that reflect the behavior of the warmest years of this period. Although such composites will not reflect the ultimate changes in the equilibrium climate that might be expected as CO_2 increases, the nature and location of regional changes may at least indicate the sign and magnitude of possible responses.

By using the experience gained by analysis and observation of the atmosphere, the rather generalized model results can be evaluated and used to develop more detailed estimates. For example, relationships between the climates of large and small regions should be useful in providing indications of changes in critical regions. The variability of recent climates also offers a means of testing the quality of the numerical models that are being used. In particular, testing the models against possible explanations of the climatic warming earlier this century may be a means of verifying whether atmospheric feedback processes are being properly modeled.

C. Climate Scenario Development

To allow an encompassing evaluation of the environmental and societal consequences resulting from increasing CO_2 and consequent climate changes,

Table IIC. Priority milestones and estimated budget requirements for research on climate scenarios

Priorities:

Intercomparison and evaluation of climate model results as a means of identifying model inadequacies, estimating uncertainties and placing limits on expected climate change.	Very High
Development of criteria and methods for interfacing data on past climates with model results in development of climatic scenarios.	High
Evaluation of other natural and societal factors that may enhance or modulate the expected CO_2-induced climate changes.	Medium

Milestones and Budget:

Fiscal Year	Milestones	Budget
1981	Workshop on methods for estimating regional climatic effects; specification of "key" agricultural and watershed regions and initiation of historical studies of detailed climatic conditions in these regions.	200
1982	Evaluate preliminary estimates of regionalized climate changes in limited number of key agricultural areas from modeling studies.	300
1983	Integrate preliminary estimates of regionalized CO_2-induced climatic effects from a variety of approaches (models, paleoclimate, historic, trends) in key agricultural areas. Prepare draft summary report.	400
1984	Composite estimates of regionalized climatic changes in key agricultural and watershed areas.	400

it is essential to develop a comprehensive estimate of changes in many climate parameters. As a minimum, such a scenario (or perhaps several scenarios of maximum, average, and minimum change) must include estimates of changes of such parameters as regional and seasonal variations of temperature and soil moisture in agricultural and watershed areas; extent of sea-ice, shelf-ice, and mountain snow; and wind stress, ocean currents, and temperatures in areas of substantial oceanic productivity. Additional factors that must be estimated will be identified in coordination with those carrying out the assessment studies.

This scenario should be based on an integrated intercomparison of the climatic changes projected by use of verified models, analysis of past climates and extrapolation of current trends. Such an effort will be an important step in looking for internal-consistency of results, for confirmation of projected changes from various modeling and historical approaches, and agreement of recent trend data with anticipated changes. The effects of using various types of models, each with their own particular assumptions and parameterizations, will need to be considered so that possible changes are not prevented and predicted changes are not merely artifacts. It is essential that scenarios for both maximal and minimal CO_2 effects be developed so that limits can be placed on possible societal impacts. Because most approaches will initially be considering climate equilibrium situations (e.g., a past warm period or a model simulation of doubled CO_2) and not the conditions occurring as the climate evolves from the present to that state, it will be difficult, but essential to estimate rates of change and the likelihood that climate change is not continuous (i.e., that the climate is transitive).

In addition to developing a consensus scenario on the climatic effects of increasing CO_2, it will be important to determine how dependent this projection is on other factors that may potentially affect the atmosphere. There are indications, for example, that increasing concentrations of fluorocarbons will decrease stratospheric ozone. The cooling of the stratosphere that can be expected from increasing CO_2 will, however, tend to increase stratospheric ozone, thereby helping counter the effect at high altitudes. On the other hand, fluorocarbons and some other emitted gases (sometimes acting through secondary species the gases interact with chemically) tend to reinforce the CO_2 climatic modifications in the lower atmosphere since these gases also tend to absorb and re-radiate infrared radiation. Aerosols, including those emitted at the surface, formed from gases in the atmosphere, or injected to high altitude by volcanoes, can also affect the atmosphere's radiative balance, and thereby the climate. Just as projecting CO_2 concentrations and climate changes is subject to uncertainty, these further evaluations will also involve uncertainties; it will still be important, however, to address these questions.

As the interest and activity in the CO_2 issue continue to mount, the need for assessing and integrating the many types and sources of information will rise dramatically. A sometimes troubling aspect of this effort will involve studies that look at only parts of the problem (e.g., the radiation balance, the biospheric effect on surface albedo), rather than at the total problem. It is not unheard of for such studies to suggest that the CO_2-induced climatic effect may be a cooling rather than a warming. Research and evaluation within this sub-element of the climate program will strive to understand and place these many studies and results into a comprehensive scenario in which uncertainties are evaluated and limits are placed on possible changes.

A variety of approaches will be used, including evaluation of past warm periods using paleoclimatic and historical data, trend extrapolation (e.g., extension of changes from 1880 to 1940), selection of warmest decade and/or warmest years, etc. Climatic changes found to be common to these different approaches and to model results will be used to construct a set of likely scenarios. Particular attention will be paid to regions where impacts may be economically or ecologically significant (e.g., agricultural regions, watersheds, mountain snow, etc.), to the seasonal effects, and to correlations of changes between regions.

D. Evidence of Climate Change

The complexity of the surface-atmosphere system, the constraints of current understanding, and the recognition that even the unperturbed climate will vary all limit our ability to use models and past climatic data to provide accurate projections of the climate into the future. It is therefore essential to seek confirmatory evidence in the current observational record. Early identification of the predicted changes would provide significantly increased confidence in the projections of later, larger changes.

Current model estimates suggest that the earth should have experienced a few tenths of a degree warming since the late 1800s due to the increase of CO_2 concentrations from about 290 to the current 335 ppm. While the variation in decadal-average Northern Hemisphere temperatures during this period has been about half a degree, the overall change over this period has been very small. Further, since the warmest decades during the last century were

Table IID. Priority and milestones and estimated budget requirements for research on evidence of climate change.

Priorities:

Identify parameters believed to be most sensitive to CO_2-induced climatic change and estimate the likelihood that the change can be identified with confidence; ensure the adequacy of the data base.	High
Expand statistical analyses of present and past climatic data in order to identify CO_2-induced climatic changes.	Medium

Milestones and Budget:

Fiscal Year	Milestones	Budget
1981	Workshop on possible research approaches to developing evidence for CO_2-induced climate change. Identification of key variables of interest.	50
1982	Expand the present limited studies.	100
1983	Preliminary statistical studies and evaluation of key variables. Prepare draft summary report.	100
1984	Preliminary evaluation of extent of change of key variables, if any.	150

the 1930s and 1940s, it is not straightforward to identify the supposed CO_2-induced change, which should be a monotonic increase. Thus, it appears that natural variations, perhaps related to such factors as intensity of volcanic activity or sunspots, currently are large enough to mask the expected CO_2 variation and that the thermal inertia of the oceans may be delaying manifestation of the rising CO_2-induced equilibrium temperature change. While a few researchers suggest that we should be able to start identifying CO_2-climate signals in the near future (e.g., Madden and Ramanathan, 1980), most experts believe that an unambiguous climatic signal of CO_2-induced effects might not be evident until the year 2000, assuming that CO_2 emission trends continue and the computer simulations are correct.

A critical question is whether more refined analysis of observations may find a statistically significant signal sooner than the year 2000 so that increased confidence can be placed in model results. There are several approaches that may provide an indication of the projected climate changes may be achievable within the next twenty years. Very large temperature responses (approximately 10°K) are projected in polar regions and the equatorial stratosphere for a doubling of CO_2. Although natural fluctuations are quite large in polar regions, we may be able to identify and isolate some of the causative factors. In the equatorial stratosphere, the data base is rather limited, but natural fluctuations are apparently rather small. (Fluorocarbon induced effects, however, may act in an opposite sense, thereby making signal identification more difficult). Finding a CO_2-induced signal in this region, however, will mainly verify the radiative prescriptions used in numerical models, and may add little confidence to projections of regional and global changes at the surface. Another possible precursor may be the minimum temperature of polar air masses, a quantity that may change more than the global average if present model projections showing an amplification of temperature change in polar regions are indicative of wintertime effects.

Certainly, projected changes in these and other parameters that are developed as part of the construction of scenarios (e.g., intensity of the hydrologic cycle, snow-line, sea-ice and permaforst extent, properties of polar ice masses, etc.) need to be compared with the observational data base in order to identify particularly sensitive indicators. It may also be useful to look at sets of parameters from the scenarios to determine whether their coupled response is in agreement with observations.

Results of these studies may point to improvements needed in current observational networks (e.g., more frequent sampling in the stratosphere, of clouds, or in polar regions). Such monitoring should be directed at providing early warning of the anticipated changes or, if absent, might reassure us that the changes have been overestimated.

Although achievement of success in early identification of CO_2-induced climate changes is not expected, it is important to lay the framework for such identification. At the least, it is important to be able to explain why such a large change as is projected for 50 years from now may not be apparent until we are halfway there. The priority would be high if success could be expected, but is somewhat less than that due to the low expectation of success. As a minimum, however, work should be initiated at high priority to throroughly review parameters that may provide an early indication of climate change.

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