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THE CARBON DIOXIDE PROBLEM: DOE PROGRAM AND A GENERAL ASSESSMENT

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TABLE OF CONTENTS

I. INTRODUCTION

While the effects of the presumably increasing CO_2 content of the atmosphere due to fossil fuel burning have been speculated on for a century, the hard data from Keeling et al. in the last 22 years have clearly demonstrated that the level of concentration is rising at a fairly rapid rate. The DOE program was instituted in direct response to this recent indication of potentially significant changes in world climate.

The DOE program falls naturally into several divisions, and is being so administered.

(1) Study of the "Carbon Cycle," the physical, chemical, and biological processes by which CO_2 is generated, maintains a quasi-balance in the terrestrial and ocean biosphere, and finally produces long term deposits of carbon in the ocean sediments and deep in the soil. Thus sources and sinks of CO_2 are to be identified and measured or estimated quantitatively. In these considerations feedback effects of increased CO_2 and rising temperature may be significant. Finally, what are the projected future CO_2 levels?

(2) Attempts to predict world-wide climate changes resulting from a significant rise in CO_2. Lacking any other guide this must be done by mathematical climate models of varying degrees of

complexity, possibly aided by analogues from past climate changes. There is a basic problem here, discussed below, of a convincing verification of these predictions.

(3) Economic and social effects of CO_2-induced climate changes. In addition to a description of the character and magnitude of regional and world-wide effects, the question of the time scale is extremely important, especially in those cases where adaptation must be the response.

(4) Environmental effects of climate change and increased CO_2. This category includes the physical and biological response to climate change; e.g., the stability of the West Antarctic Ice Sheet and the response of agricultural and natural productivity.

In the 1980 JASON Summer Study it has been our purpose to study this program to attempt some judgments on: (a) the relative importance of its components from the view of a potential national (international) policy on CO_2; (b) its progress towards these goals, including some estimate of the future time scale of this progress; (c) suggestions for additions to and implementation of the present work.

There are six parts to this report. The first is our introduction: the second our conclusions and recommendations. The third and fourth sections contain discussions of the present research programs on the carbon cycle and on climate modeling and propose some additions to these programs. The fifth section considers physical effects of CO_2-induced climate change that may be of social or economic importance. The last section considers some early warning signals for climate changes due to increased atmospheric CO_2.

Urgency: Before summarizing our conclusions we discuss here the appropriate time scale and the kinds of "urgency" in this problem. Our position, supported in the detailed argument of this paper, is as follows. We do not know of any matters which may arise from increasing CO_2 in the near future (5-10 years) which would require the attention of public authorities for possible national or international action on a large scale. *In this sense there is no immediate urgency.* The long term effects of CO_2 rise, however, are potentially serious. We have identified several needed additional projects, mostly new *monitoring observations and experiments*, for which *no time should be lost in setting them into motion.* Some of these projects, in our opinion, deserve a higher priority than do parts of existing programs. This second kind of urgency, with respect to the introduction of new observations and experiments, represents the single most important need to move the program forward. Given prompt initiation of this new work by qualified people, and with the progress of the ongoing programs, one can expect with confidence that very much more will be understood in ten years about this problem than is the case today.

II. CONCLUSIONS AND RECOMMENDATIONS

As must all programmatic studies, the DOE CO_2 project began by drawing on existing knowledge and state of the art in all aspects of its program outlined above. Thus on the Carbon Cycle, qualified persons in atmospheric chemistry, oceanography, and terrestrial biology were called on and many workshops and conferences were arranged from which a considerable literature has evolved. The existing data base for these analyses has been pretty well worked up, in our estimate, and the pressing need now is to improve greatly this data base in order to understand the reservoirs of carbonic substances and their shifts in time. A list of our proposals for this is given below. We mention first the importance of monitoring the net CO_2 production from the biosphere by direct measurement of O_2 concentration (high precision) and also the C^{12}/C^{13} ratio in the atmosphere. To complement this measurement of O_2 and carbon isotope ratios it is probably important also to undertake measurements of O_2 and CO_2 in the ocean at various depths. The flux downward of organic material in the ocean may be a hitherto underestimated sink of carbonic matter. The carbon cycle in the ocean is of such complexity that its analysis may not contribute to a detailed understanding of the atmospheric carbon cycle. A potentially important reservoir of CO_2 may be the frozen methane hydrate in the arctic tundra. The magnitude of this reservoir is certainly large; its temperature sensitivity for release of carbon should be determined. LANDSAT monitoring of forest cutting should be studied from the existing data on some understood area, and an assessment made before a committment to world-wide program is undertaken.

There has existed for some decades a well developed community of climatologists who have developed machine models of varying complexities, mostly for the purpose of describing and explaining existing world and regional climates. The CO_2 program has presented this community with the challenge to predict in as much detail as possible the changed climate with increased levels of CO_2--temperature distribution, precipitation and soil moisture, seasonal variation, altered wind patterns, possible changes in "weather". The response, in the form of numerous published papers of increasing sophistication, is now beginning to furnish rather detailed descriptions of the predicted regional climates. There remain potentially important technical deficiencies--the most obvious being the inadequate treatment of oceanic and atmospheric interaction, ocean currents, the role of the deeper ocean below the "mixed layer," and the properties of the "mixed layer" itself.

The most troubling aspect of this situation, however, is the unknown degree of credibility that should be given to a prediction of an altered climate by present day climate models, all of which have been to some extent "tuned" to present climate, and are judged by their replication of this climate. The validation of any theory in physical science lies in its predictive power; we are not aware of any such success as yet for existing climate models. The fair amount of agreement among different models and modelers does give some assurance that purely technical errors in the calculations are minimal. Possibly some "predictions" of past climates or statistically successful seasonal forecasts can be made. Without better verification from the real world, however, it will be difficult for outside observers, including public authorities, to be convinced sufficiently of the accuracy of these predictions, in regional and seasonal detail, to propose public responses when these may be unduly alarming or put misplaced burdens on society. For these reasons we believe that support for convincing verification of climate models is a more pressing question than is their further elaboration and multiplication.

The improvement of General Circulation Models by introducing better ocean-atmosphere coupling, including ocean currents and heat flow below the mixed layer, and better modeling of the mixed layer itself is taking place at present. While DOE should encourage these efforts, including the prediction of the changed "weather" as well as "climate" with CO_2 increase, we believe that the first priority for limited funds should be given to support of monitoring and experimental efforts of the kind suggested in this report.

Given the uncertainty in climate prediction, an extended program in the monitoring of climate variables should be instituted without delay. The pressure of time derives from the fact that the measurement of any climate change requires a well established baseline from which to make comparisons. (If the measurement of CO_2 concentration had extended back to the beginning of the century, instead of 1958, this whole problem would be much clearer today). Even the very simple models all agree that the CO_2-induced temperature rise increases toward the poles. Accurate circumpolar measurement of temperature should be maintained over the coming decades. It has been suggested that the thickness of the 1000 to 700 mbar layer is an accurate measure of troposphere temperature, free of many ground station errors. It has also been suggested (Charney et al., 1979) that accurate measurement of temperature in the deeper ocean layers is an indication of world-wide warming. Finally, the uncertain fate of the West Antarctic Ice Sheet (discussed below) will require on-site study and monitoring. A study of the history of the present ice shelf would be of value in a determination of whether or not it survived the post-glacial alti-thermal period. The dynamics of the ice flow in this area should be known in detail, and continually monitored satellite surveillance of the surrounding sea ice may give an early warning of possible instability.

We have no specific recommendation concerning studies on economic or social effects of CO_2-induced climate change. One may well anticipate that in a generally warmer, wetter world there will be substantial regional diversity in the changes in climate and, perhaps equally important, in weather. In the face of this diversity and the political fragmentation of the world, response may well be limited to adaptation. If these changes are rather rapid, say on a time scale of 50 years, the regional and perhaps world-wide costs may be heavy, e.g., through the effect on agriculture of a serious mismatch between climate, soil, population, and technology in various parts of the world. We believe these matters should be studied sufficiently to maintain awareness of the possibility of needed long range planning.

From the above discussion it is clear that we propose expanding the data base, initiating new experimental research, and monitoring of climate changes, rather than very greatly extending paper studies and computer modeling. A fuller discussion is given in the following pages.

Recommendations for the DOE Research Program

- (1) Carbon Cycle:
    - (a) Monitor CO_2 production in atmosphere by direct measurement of O_2 to 1 ppm.
    - (b) Similar measurement of carbon isotope ratio to 1%.
    - (c) Initial study of LANDSAT capability to determine forest output of CO_2. Method needs evaluation.
    - (d) Measurement of CO_2 in ocean to 1 part per thousand.
    - (e) Measurement of O_2 in ocean to appropriate accuracy.
    - (f) Organic flux in the ocean. Does it change?
    - (g) Study methane hydrate in frozen tundra.

- (2) Climate Prediction and Monitoring:
    - (a) Verification of GCM's description of present climate.
        - (i) Past climates? Solar fluctuations?
        - (ii) Malenkovitch Ice Age theory?
        - (iii) Laboratory study of model capability?
        - (iv) "Prediction" of distributions of seasonal climates from measured initial conditions.
    - (b) Establishment of temperature monitoring of near polar regions (1000 to 700 mbar thickness?)

(c) Study of West Antarctic Ice Sheet

  (i) Its age.

  (ii) Ice flow.

  (iii) Monitoring of sea ice by satellite.

III. RESEARCH PRIORITIES ON THE CARBON CYCLE

Introduction

Data on the mass of carbon currently stored in the major reservoirs and on the fluxes of carbon between the reservoirs, plus an understanding of the mechanisms involved, will aid in forecasting the times at which given levels of carbon dioxide are reached in the atmosphere. The essential problem in this forecasting is the small net annual flux of CO_2 into the atmosphere (2.6 Gt in 1978) compared with the separate rates of change of large reservoirs of carbon (the oceans and biosphere) that exist in nature. Only accurate monitoring of the changes in these reservoirs will make convincing forecasts possible. Such forecasts, primitive at present, could aid decision-makers in assessing the time scale which should be considered in taking possible measures to alleviate the damage or increase the benefits of an increased atmospheric carbon dioxide concentration. The priority assigned to carbon cycle research in the context of the carbon dioxide problem should be assessed in light of the following possible scenario: monitoring of atmospheric carbon dioxide over the next decade shows a continued exponential rise at a rate equal to or greater than the rate of use of carbon based fuels. Despite a lack of understanding of the details of the carbon cycle, there would be increasing social and political pressures for a policy response which might well include some modification of our present carbon based fuel usage. A description of the carbon cycle is important but not necessarily essential to deal with the long term carbon dioxide problem. In addition to understanding the mass of and fluxes between reservoirs, it is also desireable to be able to predict approximately how these quantities change as atmospheric carbon dioxide increases. Temperature increases will alter the reservoir characteristics of the various reservoirs as will the changes in the atmospheric carbon dioxide concentration.

The Large Reservoirs of Carbon

By far the largest reservoir of carbon is the geologic one where carbon is stored in sediments and igneous rocks ($\sim 1 \times 10^8$ Gt). The magnitude of this reservoir is uncertain perhaps by as much as a factor of five. Since only a small fraction interacts with the atmosphere and oceans, efforts to lower the uncertainties in the absolute magnitude of this reservoir have a low priority.

Methane hydrates trapped in permafrost regions on land and in ocean sediments probably constitute the second largest reservoir of 10^5 Gt (Yo, Makogan, Hydrates of Natural Gas, Geoexplorers, Inc., Denver, 1978). This estimate is uncertain by a factor of ten since little work has been conducted on methane hydrates outside of the Soviet Union. The magnitude of the terrestrial methane hydrates reservoir is about 2×10^3 Gt, again uncertain by a factor of ten. This reservoir, which could contribute a positive feedback in a warming climate, has been neglected in carbon cycle considerations. Efforts to estimate this terrestrial reservoir should be supported. A large amount of data exists as a result of petroleum exploration and production in the Artic regions of North America. These data could be used to obtain estimates of the total extent and depth profile of methane hydrates, but the data have not been analyzed in terms of carbon cycle considerations.

The oceans contain about 4 x 10^4 Gt with an uncertainty of about ten percent. A fraction, about 580 Gt of inorganic carbon, resides in the "mixed layer." The magnitudes of these reservoirs are probably well enough known for present carbon cycle considerations. We note, however, that the conventional picture of a "mixed layer" with a fixed thickness can be misleading and that seasonal fluctuations in the thickness of the "mixed layer" may significantly affect the deposition of carbon in the "intermediate layer" and the deep ocean. The organic carbon content of the mixed layer is not well known.

Recoverable carbon based fuels constitute a reservoir of about 7 x 10^3 Gt with an uncertainty of at least a factor of two. This reservoir is large enough to fuel the world economy for centuries so that improvements in the estimate of the magnitude of this reservoir are not needed for carbon cycle considerations.

The soils form a large reservoir of carbon (1.6 x 10^3 G ton ± 30%) which could be released to the atmosphere by deforestation and warming. A vast amount of literature exists on soil carbon, yet there are sparse data on the relative world-wide distribution of the carbon compounds, "inorganic" carbon, humic acid, etc. These data are needed to estimate the rate of release of carbon as a result of warming or deforestation. Because of the wide variety of soil types, securing world estimates of "mobile" carbon will require extensive sampling and chemical analysis.

The living biosphere contains 800 G tons of carbon with an uncertainty of about 20%. This overall uncertainty may not be important but the magnitude of carbon stored in various ecosystems may be.

The atmospheric reservoir is the smallest (705 Gt) but the best known as a result of a dedicated effort over the past twenty years by Keeling and his co-workers. It is of fundamental importance that the observations at Mauna Loa and the South Pole of atmospheric CO_2 be continued. However, we see little value in setting up numerous new stations since the stations at Mauna Loa and the South Pole show high coherence. Continued observation at Point Barrow may be helpful because of the large seasonal fluctuations that have been observed there.

Fluxes Between Reservoirs

The balance sheet for the carbon cycle can be represented as

$$A = F - B + D - S \tag{1}$$

where A is the annual increase in atmospheric CO_2; F is the annual release of CO_2 in the burning of carbon based fuel and in cement manufacturing; B is the net increase of biomass and soil carbon which may be in response to the increase of atmospheric CO_2; D is the decrease in biomass and soil carbon produced by deforestation and erosion; and S is the net annual flow of CO_2, both inorganic and organic, into the oceans.

As has been noted, A is the best determined flux and every effort should be made to maintain over the next decades a program for determining the concentration of atmospheric carbon dioxide as a function of time.

F is now determined using United Nations data which are in turn derived from submissions by individual nations. We would estimate that the total values are probably accurate to about five percent, and efforts to reduce this uncertainty are not warranted given the larger uncertainties in B , D , and S . Forecasting the world's future energy requirements would require a model of the future world economy. It is unlikely that definitive models would be developed given our present limited understanding of the interaction between energy demand and economic growth and the sensitivity of economic growth to political factors. Additional research on better forecasting of world energy requirements and the fuel mix a decade in advance is not something that the DOE carbon dioxide research effort need support.

The method that has been used for estimating the biospheric carbon flux has been to work from surveys of the historic and field records to determine the past and present size of various types of forests, the changes in cultivated land area, etc. The uncertainties are such that estimates of the annual (positive) flux of CO_2 into the atmosphere from this source range from 0.8 to 8 Gt. In view of the Keeling measured net flux of 2.6 Gt/yr. this spread of estimates is discouraging, and it is not clear how much it can be improved or how quickly.

Two methods have been proposed to measure the biospheric contribution (- B + D). In one approach LANDSAT imagery would be used to determine year by year like changes in the world forest. This method has several disadvantages. Ground truth must be obtained for the many individual kinds of forest since LANDSAT photography gives only foliage coverge which is itself difficult to interpret. The tree type and the amount of wood in the standing crop must be determined by ground observation. A second disadvantage is that photography does not directly provide data on loss of carbon from soils. A soil model must be used and we are concerned whether a few such models could treat adequately the wide variety of forest and soil types. A third difficulty lies in handling the very large quantity of data provided by LANDSAT. Almost certainly a world survey would require development of automated data handling, a major task by itself.

The second method relies on the fact that the burning of carbon-based fuels and deforestation and erosion remove oxygen from the atmosphere through the formation of carbon dioxide. Of the terms in the oxygen balance sheet, the rates of change of oxygen in the atmosphere and the ocean are not known. The determination of oxygen in the atmosphere to a part in 10^6 and in the oceans to a part in 10^3 over a number of years could provide new insight into the role of the biosphere in the carbon cycle. For the atmosphere, the present stations could be used.

During our study we heard a report from P. Tans of Lawrence Berkeley Laboratory on preliminary work using Raman scattering to determine the O_2/N_2 ratio to one part in 10^6. His group demonstrated that its laser source has the needed stability to carry out the precision measurements required. This Raman spectroscopy method will be funded by DOE and NOAA. We would give very high priority to this project, because its success would resolve so much. Determination of changes in oxygen levels in the oceans presents a lesser analytical problem but a greater sampling problem. The oxygen chemistry in the oceans is simpler than carbon chemistry but local oxygen concentrations will depend on the ambient level of biological activity. Determinations of trends in the ocean's oxygen concentration will require repeated observations at various stations away from coasts and from regions of nutrient-rich upswellings. The monitoring of oxygen in the oceans and atmosphere is of highest priority in understanding the carbon cycle.

An uncertainty in the oceanic carbon flux lies in the rate at which organic carbon is transferred from the euphotic zone to the deep ocean as particulate matter. The required observation involves determining the rain of particulate matter. As in the case of determining the oceanic oxygen content, the total rain of particulate carbon will require observation at a number of localities over several years. It would be of particular interest to determine whether or not the seasonal variation, primarily in productivity, shows up as fluctuations in the rain of carbon. Research on the movement of carbon in the oceans deserves a high priority.

Possible Feedback

The size of the large reservoirs of carbon may change in response to increased levels of carbon dioxide in the atmosphere. The magnitude and even the sign of these changes are uncertain.

The biosphere can be expected to respond both to the change in carbon dioxide and to the temperature. An extensive amount of literature exists on the response of plants to increases in carbon dioxide concentrations in atmospheric growth chamber experiments, though lack of documentation on temperature, moisture and nutrients reduces the value of much of this experimentation. A few field experiments have been carried out under plastic tents. The relevance of these data is uncertain since most of the world's biomass is in the form of forest. The direct observation of enhanced carbon levels on the growth of a tree during its lifetime poses substantial challenge. Progress in this area is likely to come from observations on the oxygen cycle and from a better understanding of the photosynthetic process in trees. We note that there exists a large community of researchers in this area who have not been brought into discussions of the future carbon cycle.

Similar large uncertainties exist with respect to the impact of climate change on net productivity. Agricultural scientists have carried out regression analyses attempting to separate the effects of changes in precipitation, temperature and fertilizers. These analyses provide a rough estimate of how agricultural productivity may change in response to alteration in climate. However, such analyses have not been applied to natural systems so that the response of these systems to climate change is not known. It may be productive to initiate such analyses using areas that have been studied over a number of years.

The thermal response of soils is very poorly known. The presumed increased rate of oxidation and the upward diffusion of carbon dioxide could be large enough to be of consequence in considering future carbon dioxide levels. Measurements are needed on the rate constants for the oxidation of the various organic compounds in soil as well as the diffusion constant as a function of depth. The problem is complicated because of the great variety of soil types.

The recognition that large quantities of carbon may be trapped as methane hydrates is relatively recent and the role of methane hydrates in the carbon cycle has not been investigated. Besides determining the magnitude of the reservoir, which has been discussed above, there is a need for analyses and measurements of the response of methane hydrates in permafrost as a result of changes in mean temperature.

IV. ON THE PREDICTION OF NEW ENVIRONMENT FROM A GIVEN RISE IN ATMOSPHERIC CO_2 AND OTHER IR ABSORBING GASES RELEASED BY FOSSIL FUEL BURNING

Criteria

For a climate model reliably to give the response of our environment to a large increase in atmospheric CO_2 it should ideally be able to predict all of the following:

(1) The change in important globally- and time-averaged climate variables such as temperature $(\overline{\overline{\Delta T}})$ and rainfall $(\overline{\overline{\Delta R}})$. Does the earth heat up? By about how much? What is the time dependence for achieving the new average climate in response to a known atmospheric change? Because of ocean thermal inertia, will the climate change much more slowly than atmospheric CO_2?

(2) The latitude (θ) dependence of these changes $\overline{\Delta T}(\theta)$, $\overline{\Delta R}(\theta)$. What are the relative effects in temperature and rainfall in temperate, tropical and polar regions?

(3) The full dependence of these climate properties upon latitude (θ) and longitude (ϕ) : $\overline{\Delta T}(\theta,\phi)$, $\overline{\Delta R}(\theta,\phi)$, etc. Where will it become hotter and drier, hotter and rainier, etc.? How does soil moisture change?

(4) The diurnal and seasonal dependence of these changes. How do night frost lines change? Or maximum summer temperatures? Or spring rains?

(5) The spectrum of large scale fluctuations about the climate average (weather statistics). What is the changed frequency of droughts in various regions? When will they occur simultaneously over very large areas of a continent? How often will winters be exceptionally severe or rain rot crops at harvest time? What is the new probability for rare dramatic fluctuations in continental season weather?

(6) How will the frequency and development of detailed weather patterns in space and time change from contemporary ones? Where and how often will there be frequent large blizzards, tornadoes, hurricanes? Will precipitation be in prolonged gentle drizzles or rarer large downpours? And at what times in the day?

These criteria for a successful model for the environmental impact of a changed atmosphere on climate variables are listed in order of the difficulty for achieving them. Criterion (1) is certainly insufficient for predicting impacts upon agricultural activity and the quality of life. We would need to achieve at least (3) and (4), would very much want (5), and should like to have (6), but the latter would not be crucial for decision making.

Status

(1) There is a present consensus among modelers (but not yet complete unanimity even here) that the earth's surface will heat up as the atmosphere is made more opaque to reradiated IR. For, say, a doubling of atmospheric CO_2 without any large change in other absorbers except water vapor, there is a convergence among realistic models to a global average temperature change $\overline{\overline{\Delta T}} = 3 \pm 1^0C$. There are many complicated feedbacks which, if completely and quantitatively understood, might still change the quantitative estimates, perhaps even by a factor of two. Thus, for example, a hotter surface gives more evaporated water vapor and thus even more IR absorption but the concomitant increased cloudiness could increase reflected sunlight and alter details of IR radiation into space from cloud tops. But such negative feedbacks exist only if driven by an increased surface temperature (although one can still find some meteorologists who claim that they are not yet absolutely sure even of the sign because of uncertainties in cloud physics; they do not make models). How increased surface temperatures over water increase evaporation rates depends sensitively upon surface wind speeds as well as temperature. There is a concensus that $\overline{\overline{\Delta R}}$ should also increase with increasing atmospheric CO_2 but the qualitative and quantitative results are less firm. Because of uncertainties in heat transfer within the ocean and large thermal inertia effects that may be associated with it, the time scale for achieving the new steady climate is not clear and may even take decades.

(2) Modelers agree that $\overline{\Delta T(\theta)}$ increases, probably monotonically by a factor of about 3, as one goes poleward from the equator although the earliest models exaggerated this effect. The physical causes of this increase, such as albedo changes from reduced ice, are qualitatively understood. Quantitative reliability can come only when the role of oceans in zonal heat transfer and especially any changes in heat transfer, in response to increased CO_2 effects, are included in calculations. This has not yet been attempted.

(3) Only General Circulation Models (GCM) which include earth surface topography can hope to meet the criteria for regional prediction. Several, led by the GFDL model, have achieved very considerable success in describing our present climate, and are being used to predict the changes in climate which should be caused by changes in atmospheric CO_2. How much confidence can we put in such theoretical models when there are no experiments to test them except agreement with present climate? One problem is that there is always a certain amount of tuning of models to give present climate; even when the number of empirical parameters is minimal, there is always some "parameterization." A model will, and should, be "improved" until it gives a reasonable description of present climate but there is much less reason to continue to "improve" it beyond that state. A second problem is that although the dynamical changes of the atmosphere are described in the models by appropriate Navier-Stokes equations, this is not yet

true of the vast oceans with which the atmosphere is in contact. Ocean currents and the interzonal and longitudinal heat flow they support are not in the GCMs. Nor is an unparameterized consideration of vertical mixing and heat transfer. Thus, for example, mixed layer thickness depends upon wind velocity and storm frequency and intensity. Since all of these will vary with the thermal effects of increasing atmospheric CO_2, the future ocean may have a significantly altered parameterization of its role in atmospheric effects. But even a presently appropriate parameterization of ocean effects good enough for confident "forecasting" of all regional climates is unavailable. The construction of the ocean climate models to be married to atmospheric ones is, at best, only beginning now and the data needed to test ocean models are very much less extensive than that for atmospheric ones. The importance of wind carried thermal energy between land and sea in establishing continental climate suggests that regional effects are very much more sensitive to an adequate treatment of ocean climate than are average zonal ones. It is difficult to believe that confident, reliable predictions of new regional climates altered from present ones by added atmospheric CO_2 will be available in less than a decade, if then.

(4) Although some GCMs include seasonal effects, they generally do not yet explore diurnal variations. Except for expense there is no reason in principle to preclude such calculations. But much more of a burden will be put on reliable accurate descriptions of

all relevant phenomena which can and do occur on very short time scales, e.g., cloud formation and dissipation, water-land heat transport by winds, etc.

(5) There is very little published work on steady state fluctuation about the GCM climate means, and none, yet, on the computed regional changes in these fluctuations in response to altered atmospheric CO_2. It is not yet certain the observed computer model fluctuations can be identified with weather or even with somewhat longer time scale anomalies in seasonal weather. Because GCMs have relatively coarse grids, numerous round off errors, approximate parameterized descriptions of convection, poor representations of sea surface dynamics, etc., even if they turn out to give adequate descriptions of climate, means they may give poor descriptions of the fluctuations about them. (Special problems may arise if observed weather fluctuations originate in very small scale variations below the grid size.) But even if GCMs were to reproduce, say, the first and second moments of regional weather correctly, this would be insufficient to demonstrate that GCMs can produce an adequate description of the occurence of relatively rare regional anomolies--the exceptionally severe winter in New England, the extraordinarily hot summer drought in the lower plains states--or even of the expected extremes during typical seasons. Unfortunately until this very important and difficult question is resolved it will not be possible to make definitive statements about the environmental effects on specific regions from increasing atmospheric CO_2.

(6) Although reproduction of the typical future global and regional weather map sequences would be useful, they are hardly necessary for environmental impact assessment except, perhaps, as a good test that GCMs for the present atmosphere are a correct description. (However, such quantities as hurricane frequency will clearly be important in some regions.) We seem to be a long, long way from achieving this.

Suggestions

(1) Encouragement of and perhaps support for an ocean climate model for currents, heat transport, regional sea surface temperatures, etc. These should include effects of phenomena like seasonal sea-ice melting which may be particularly sensitive to a polar warming. Ocean models lag atmospheric GCMs and will probably limit their predictive abilities even if there were no other problems.

(2) Exploration of the relationship between fluctuations of climate in GCMs and weather. Where do the fluctuations come from? Are they sensitive to altered numerical techniques, grid sizes, etc.? How do GCM pattern fluctuations compare to the known time sequences of weather maps? To the extent that GCMs do describe atmospheric dynamics, one might expect them to give seasonal forecasts from initial measurements with some "skill".

(3) Continued support for comparing climate indicators when atmospheric CO_2 was very different (e.g., 70,000 BP) with GCM calculations of those climates.

(4) The construction of some reasonably complicated table top experiment which, although it is in no sense an analogue of the earth's atmosphere, does contain many of its essential ingredients such as convection, differential lateral heating, Corolis forces, evaporation, etc. Can a GCM be constructed to describe this "climate" and to predict how it changes in response to parameters which can be varied? How well can such GCMs do in this simpler problem? Note there is no intention in this proposed experiment to "scale" the real earth.

V. EFFECTS OF CO_2 CHANGED CLIMATE

Some predicted effects of CO_2-induced climate change may have severe impacts on human life. These predictions are based on climate models of the kind discussed in previous sections. The credibility of these predictions is not established. Only the more general conclusions, such as world-wide temperature rise can be accepted with confidence at present. The time scale of these changes is even more uncertain; yet this is of enormous importance for adaptation of man's activities to a new environment.

The first potentially significant change we are concerned with depends upon stability of the West Antarctic Ice Sheet. This massive body of ice is grounded on bedrock which lies below sea level. A significant polar temperature rise induced by increased CO_2 in the atmosphere would heat up the waters at the edge of the ice sheet which, after melting back the sea ice on a time scale of decades, would begin undercutting the ice shelves and ice sheet. A complete collapse of the West Antarctic Ice Sheet would raise global sea level by 5-6 m and flood 25% of Florida, 30% of Louisiana, and 10% of New Jersey. There is no general agreement on the minimum time scale for the collapse of the West Antarctic Ice Sheet. Most estimates put the time on the order of 100 years or more after a general warming has taken place, but it may take millenia or, because of increased snowfall, not occur at all.

Much can probably be learned about the future of the West Antarctic Ice Sheet by determining how long it has been there. When has it been absent and what was the climate like at those times? In particular, was it present in the alti-thermal period about 7000 years ago when global temperatures were about 1° C greater than today? Beyond historical research such as this we are of the opinion that continuing to monitor the extent of sea ice and the size of the Ross Ice Shelf is the major activity which should be supported by DOE. The disappearance of these is expected to be precursor to possible collapse into the sea of the ice sheet. If they disappear, we may have some time, perhaps 100 years, to deal with the ice sheet. At a DOE workshop in Orono, Maine, in Spring, 1980, an extensive research program of observation stations, satellite monitoring, and drilling in the West Antarctic was proposed. No cost estimate was attached but it appears a costly enterprise to undertake at present when so much else is questionable about the CO_2 problem.

A second significant potential consequence is the possible effects on agriculture and grazing land from CO_2-induced changes in temperature, precipitation and soil moisture, seasonal weather, etc. GCM calculations indicate patterns of world-wide shifts in these quantities. Credence in the details of these predictions must be limited at the present time, for the reasons discussed in Section II. While the net long range effect of these changes of agricultural production, for example, is unclear, it seems likely that there may well be serious mismatches in many regions among climate, soil quality, population, technical support facilities, for two generations or more after CO_2 warming sets in. Surely some serious thought on the beginnings of long range planning is called for.

Similarly, large scale changes in water supply and irrigation systems may be needed in many parts of the world. The uncertainties as to detailed prediction apply here also. The investment involved is huge; long range planning is called for.

Another possibly serious effect of polar warming would be the <u>disappearance of sea ice.</u> The seasonal formation of this ice from salt water constitutes a crucial pump to the lower levels of the oceans. Disappearance of this pump would interrupt the sea currents and oceanic upwelling via many parts of the world.

VI. EARLY WARNINGS OF CLIMATE CHANGE

One would like to have as early a warning as possible of climatic change resulting from increased atmospheric CO_2. We have identified several possible indicators that may have an exceptionally large signal or a notably low noise level. The search for low noise early warning signals is important.

All model calculations agree that the surface warming in the polar regions will be much enhanced over equatorial or temperate temperature rises. A systematic monitoring of atmospheric temperatures in polar regions seems to be very much called for. The climatic deviation of global temperatures from the mean over the last century has been $\lesssim 0.5^0$ C. The rise in polar temperatures resulting from doubled atmospheric CO_2 may be as high as 6-10° C. The signal should be large. In the same vein careful monitoring of the extent of sea ice extent is called for. This is a most sensitive part of the earth's cryosphere and significant retreat will certainly be a signal of climatic change.

It has been suggested that a sensitive measure of atmospheric temperature is the thickness of the 700-1000 mb layer in the atmosphere. 700 mb is about 3-4 km above the earth's surface, so we are measuring here a quantity integrated over the troposphere. Such a quantity is likely to be less sensitive to ground station geography and local surface weather. Thus it will be a low noise signal. In discussions with our study group,

J. Namais suggested that the thickness of this layer would sensitively measure changes in temperature of ± 0.5° C.

Another low noise signal suggested as a good early warning of climate change is the temperature of the ocean waters just below the mixed layer. This depth is not strongly coupled to the noisy atmosphere which creates the mixed layer in the first place. Since increased atmospheric temperatures will be moderated by the enormous heat capacity of the ocean, a temperature rise in the oceans should be a rather clear signal of climate change.

Climate models have suggested a shift poleward of precipitation patterns and distribution of soil moisture as a result of increased CO_2. These quantities are of clear general importance to society and will no doubt be monitored carefully. We have no sense that they qualify as particularly good early warnings of CO_2-induced climate changes.

Finally it has been suggested that significant stratospheric cooling should accompany increased atmospheric CO_2. The reason is simply that the stratosphere is hot because it lacks a good means to radiate energy deposited there by solar photochemical processes. Additional CO_2 in the stratosphere would certainly provide a good radiator and cool it by perhaps several degrees. One can probably regard stratospheric cooling as mostly a measure of increased atmospheric CO_2 with fixed ozone and not certainly as an indication of climate change accompanying that increased CO_2. Indeed, if the stratosphere does not cool as CO_2 is increased with fixed ozone density, it would require a re-examination of some of our basic understanding of the effects of CO_2 on atmospheric radiative properties.

During the course of our study many qualified persons interested in the issue of climate change resulting from increased atmospheric carbon dioxide have come to share their knowledge and time with us.

(1) In consideration of the global carbon cycle we heard from:

P. Tans, Lawrence Berkeley Laboratory
W. Elliott, NOAA
W. Schlesinger, UC Santa Barbara
G. Woodwell, Woods Hole
R. Rotty, Institute for Energy Analysis

(2) Climate modeling was reviewed and updated for us by:

V. Ramanathan, NCAR
S. Manabe, NOAA-GFDL
R. Dickenson, NCAR
S. Schneider, NCAR
M. Mac Cracken, LLL
R. Cess, SUNY Stony Brook

(3) Economic and social effects of CO_2 induced climate change were discussed by:

S. Schneider, NCAR
C. Cooper, San Diego State University
R. Revelle, Scripps Institute of Oceanography

In addition, J. Namais of Scripps, and R. Revelle spent a considerable number of hours making clear the intricasies of climatic, social, and economic predictions. During the full course of our study R. Dahlman of the DOE Carbon Dioxide and Climate Research Program sat with our study group and aided us enormously in making many points clear. He also provided us with a most useful overview of the DOE effort in this important matter.