United States Department of Energy

Office of Energy Research
Office of Basic Energy Sciences
Carbon Dioxide Research Division
Washington, DC 20545

DOE/ER-0316
March 1987
Dist. Category UC-11

DOE/ER--0316

DE87 012757

Master Index for the Carbon Dioxide Research State-of-the-Art Report Series

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MASTER

DISCLAIMER

FOREWORD

Publishing the SOA series has been a rewarding experience for all of us. The hundreds of reviews received before publication, the positive comments received after the reports were published, and working with the coordinator/editors, authors, and support staff has reaffirmed for all of us the team spirit needed to scrutinize and analyze the body of science on CO_2 and the greenhouse effect.

We have made these reports available to many individual scientists and policy makers who are concerned about the consequences of increased atmospheric CO_2 concentrations. Over 3,000 copies of the reports have been sent to researchers in 150 countries. To ensure that these reports are available for some time in the future, hundreds of libraries, training centers, and information centers were sent the complete series of reports. Of the libraries, 219 in the USA and 126 foreign libraries in 49 countries received copies. The SOA reports are now available in about 90% of the world's countries.

Publishing the SOA series has also been a learning process for all of us. We are indebted to the many authors and reviewers for giving us their expert knowledge on the many complex problems related to the CO_2 issue.

We at the U.S. Department of Energy would particularly like to thank the coordinator/editors for helping us through the process of reducing the vast body of scientific information on CO_2-climate interactions. Again our thanks to Jennifer D. Cure, Frederick M. Luther, Michael C. MacCracken, Mark Meier, Boyd R. Strain, John R. Trabalka, and Margaret R. White.

Without the help of these many scientists, we would not be in a position to prepare our research plans for the next decade.

Finally, we want to acknowledge the invaluable assistance of Dr. Fred and Linda O'Hara who prepared the index to each volume in the SOA series.

Frederick R. Koomanoff, Director
Carbon Dioxide Research Division
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U.S. Department of Energy

PREFACE

If the concentration of carbon dioxide (CO_2) in the atmosphere continues to increase, the Earth's climate could be modified with attendant effects on human health and natural resources such as agriculture, forests, fisheries, and water. To assess the effects of this increase, scientists must deal with two difficulties: the enormity of the problem and the diversity of the disciplines contributing to its solution. This enormity and diversity make it difficult to (1) define the problem, (2) develop strategies for solving the problem, and (3) establish communication and cooperation among the researchers working on different facets of the problem. Therefore, the compilation, integration, interpretation, and dissemination of information are especially important.

It was to aid this compilation, integration, interpretation, and dissemination that the four State of the Art (SOA) reports, *Atmospheric Carbon Dioxide and the Global Carbon Cycle, Direct Effects of Increasing Carbon Dioxide on Vegetation, Detecting the Climatic Effects of Increasing Carbon Dioxide,* and *Projecting the Climatic Effects of Increasing Carbon Dioxide,* and the two companion reports, *Characterization of Information Requirements for Studies of CO_2 Effects: Water Resources, Agriculture, Fisheries, Forests and Human Health* and *Glaciers, Ice Sheets, and Sea Level: Effect of a CO_2-Induced Climatic Change,* were published by the U.S. Department of Energy's Carbon Dioxide Research Division. These reports were produced in February 1986, March 1986, February 1986, April 1986, July 1986, and October 1985, respectively. However, to make reference easy and to allow more effective bibliographic control, they were given the same date of publication, December 1985, except for *Glaciers,* a version of which was previously published by the National Research Council and which still bears that agency's date of publication.

Considerable information on atmospheric carbon dioxide and its possible effects on world climate is summarized in these six volumes. Each volume has its own index, but to make the information that is distributed throughout the six volumes more accessible and usable, comprehensive citation and subject indexes have been compiled. The subject indexes of the individual volumes have been edited to provide a uniformity from volume to volume and also to draw distinctions not needed in the separate volumes' indexes. For example, the term "Accumulation" clearly refers to biomass carbon in the Global Carbon Cycle and Direct Effects SOA volumes and to glacial snow and ice in the Glaciers/Sea Level volume. But in the comprehensive subject index, the distinction between "Accumulation of carbon" and "Accumulation (glacial)" must be made. Also, the comprehensive subject index has been formatted in a matrix arrangement to graphically show the distribution of subject treatment from volume to volume. Other aids have also been provided to allow the reader to make comprehensive and convenient use of the six volumes. These aids include cross references between the scientific and common names of the animals and plants referred to, a glossary of special terms used, tables of data and conversion factors related to the data, and explanations of the acronyms and initialisms used in the texts of the six volumes.

Finally (but actually presented first), the executive summaries of the six volumes are collected and reproduced here to allow the readers interested in the contents of one volume to rapidly gain information on the contents of the other volumes.

I would like to thank Dr. Frederick O'Hara and Linda O'Hara for their work in compiling and checking the citation and subject indexes, Laura O'Hara for her work in producing the scientific and common name indexes, Michael O'Hara for performing the makeup of this comprehensive index volume, and Dr. Bruce Ewbank for the computer preparation of the subject-index information for phototypesetter output. I would also like to thank Dr. Raymond Millemann, Donna Stokes, Tammy White, Cheryl Buford, and the rest of the staff of the Carbon Dioxide Information Analysis Center for their assistance throughout the SOA process.

Michael P. Farrell, Editor

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EXECUTIVE SUMMARIES

ATMOSPHERIC CARBON DIOXIDE AND THE GLOBAL CARBON CYCLE

Carbon dioxide (CO_2) in the atmosphere appears to play a major role in determining the Earth's climate and habitability through regulation of the solar radiation balance. Atmospheric CO_2 levels have increased approximately 25% from 1800 to 1985, attributable mainly to human influences, first from deforestation during the massive global expansion of agriculture, and now primarily from fossil fuel burning. A significant and disproportionate fraction of the overall increase has occurred, since the beginning of systematic atmospheric CO_2 measurements in 1958, during a period of unprecedented fossil fuel use. A doubling of the atmospheric CO_2 level of 1800 may produce a global average temperature warmer than during any period in the last 100,000 years or more, and the CO_2-induced warming ("greenhouse effect") could be augmented significantly by increasing levels of other atmospheric trace constituents.

This volume focuses on the global cycle of carbon, the dynamic balance among global atmospheric CO_2 sources and sinks, which determines the rate of increase in the atmospheric CO_2 concentration. The observed increase in CO_2 content of the atmosphere is less than the estimated release from fossil fuel consumption and deforestation because of interactions between the atmosphere and other global carbon reservoirs. These interactions must be understood to provide a basis for developing models that will project future changes in atmospheric CO_2 concentration as fossil fuel use continues. The carbon reservoirs that are known to be important in the response to anthropogenic CO_2 are the atmosphere, the ocean, and the terrestrial biosphere including soils.

Predictions of future atmospheric CO_2 concentrations must be based on carbon cycle models that accurately depict quantitative rates of carbon exchange among the major global reservoirs. As a first approximation in the validation of models, it should be possible to compute a balanced global carbon budget for the contemporary period; to date this has not been achievable and the reasons are still uncertain. Terrestrial land-use changes, principally deforestation, have contributed to the rise in atmospheric CO_2 levels, but current mathematical models of the global carbon cycle cannot accommodate contemporary biospheric releases in addition to fossil fuel releases. Thus, these models produce estimates of past atmospheric CO_2 levels that are inconsistent with the historical atmospheric CO_2 increase. This inconsistency implies that significant errors in projections are possible using current carbon cycle models.

Detailed histories of atmospheric CO_2 obtained from ice cores indicate that significant nonfossil CO_2 sources existed in the 19th century. Strong evidence exists that deforestation in the 20th century has been as intense as that in the 19th century, even though the focus of clearing has shifted from temperate to tropical regions. Thus, there appear to be several possible, perhaps complementary, explanations for the observed inconsistency in modeling: (1) undiscovered errors in the time sequence of terrestrial land-use changes; (2) existence of additional contemporary sinks not represented in current models; and (3) masking of existing sinks by oversimplified terrestrial and ocean models. All three could be valid, each partially obscured by the others, as one simple answer.

Although the carbon cycle has been controlled by a system of checks and balances, small, naturally occurring differences in the annual sums of sources and sinks led to significant changes in atmospheric CO_2, long before land-use changes and fossil fuel burning by humans began. Over the past 100 million years, atmospheric CO_2 levels are thought to have been regulated primarily by the balance between (1) CO_2 releases from biogenic carbonate precipitation in the ocean and from tectonic processes and (2) CO_2 uptake by organic carbon burial in sediments and by mineral weathering processes. Natural changes in the rates of these processes or in the resultant flux differences (respective sums of sources and sinks) are generally thought to be too slow to significantly affect atmospheric CO_2 levels over the next few centuries. However, it is not yet clear that we have a satisfactory understanding of what drives this slow-breathing system upon which shorter term human perturbations have been imposed, this flywheel that has kept the Earth habitable for billions of years. Human effects on atmospheric composition and on the size and operations of the terrestrial ecosystems represent major perturbations to the life-support system crafted in nature. The opportunity to provide more evidence of its self-regulation (e.g., through natural feedbacks involving the biota) should be welcomed, especially if that were to moderate the human cost of regulation or adaptation to change.

Understanding the carbon cycle of the globe requires very different approaches than does the solution of more traditional, experimental scientific problems. Industrialization and changes in the landscape have disturbed natural biogeochemical cycles of carbon and nitrogen, another element of climatic interest, for several centuries. Evaluating what happened and what may happen in the future requires understanding of previous conditions that existed when there was less fuel burning, forest harvesting, or farming, reaching back past millennia of human population expansion, past the glaciations of the last million years, and through many millions of years while fossil carbon was being banked in the stratigraphic column. Development of a knowledge base for the carbon cycle requires that (1) a variety of recorded historical and contemporary changes in atmospheric CO_2 concentration needs to be understood; (2) the fossil fuel, biospheric, and oceanic interactions with the atmosphere, expressed as fluxes, need to be quantified; and (3) models that can accurately represent the major fluxes over time need to be developed for interpreting the past and predicting the future.

HISTORY OF ATMOSPHERIC CO_2

From 100 million years ago until the end of the last ice age 10,000 years ago, very large and as yet poorly understood changes in the atmospheric CO_2 level are thought to have occurred. From an initial concentration perhaps as high as several thousand parts per million (ppm) suggested by long-term geochemical modeling exercises, the atmospheric CO_2 level fell gradually toward much lower values of 200-300 ppm characteristic of the glacial-interglacial cycles of the past million years. Analyses of sedimentary carbon isotope records indicate that the CO_2 level varied in a regular, periodic fashion, cycling at the ice age frequency of about 100,000 years between a low near 200 ppm in cold, glacial phases and a high near 270 ppm (but up to 350 ppm) in warm, interglacial phases, several times during the last million years.

The anthropogenic increase in atmospheric CO_2 concentration from within a range of 260-285 ppm in 1800 to 345 ppm (est.) in 1984 is approaching, but has not yet exceeded, the apparent limits of natural variation characteristic of the glacial-interglacial cycles of the past million years. Past relationships between atmospheric CO_2 levels, reservoirs of the global carbon cycle, and climate change have been inferred from a variety of methods, including ice core records for the period from the last major glaciation to the present day. An accurate characterization of such relationships may be critical for understanding some future responses of the carbon cycle and climate to human perturbations. The ice core records appear to provide the best source of information on atmospheric CO_2 (and trace gas) fluctuations over the 50,000-year period prior to the Mauna Loa record. Currently inexplicable, but provocative, rapid fluctuations (~70 ppm over a century), strongly correlated with oxygen isotope indices of climate change, are recorded in a Greenland ice core formed during the last full glacial period.

On time scales of recent decades to centuries, for example, from 1800 to the present, human impact on atmospheric CO_2 and the global carbon cycle becomes clearly measurable in ice cores, in tree rings (carbon-14 depletion), in the atmosphere, and in the surface ocean. A much-expanded, international CO_2 measurements network is now documenting a global concentration increase, at an annual rate averaging 1.5 $\pm$0.2 ppm (3.2 x 10^{15} g C). The atmospheric increase since 1958 represents an amount equivalent to 58 $\pm$5% of the total fossil fuel CO_2 released. This atmospheric record shows potentially important long-term changes, for example, the increasing amplitude of the seasonal cycle and year-to-year variations whose significance is not yet well understood. A synthesis of the atmospheric measurements from around the world currently represents the most precise and integrated record available of the workings of the global carbon cycle, of the fluctuating regional CO_2 exchanges of the atmosphere with both the ocean and the terrestrial biosphere, and of the response of this complex system to strong perturbations of both natural and human origins.

The available data on past fluctuations in atmospheric CO_2 and climate suggest that our current carbon cycle models, which emphasize human perturbations, may be missing natural feedback components involving both terrestrial and marine systems, perhaps even climate-induced "mode switches" in ocean circulation patterns, which could be very important in understanding changes in both climate and the carbon cycle over the next century.

Recent ice core research has narrowed the uncertainties in the historical record of atmospheric CO_2 variations over the past 200 years, but current uncertainties still do not permit an adequate definition of the magnitude and timing of either nonfossil CO_2 sources or carbon sinks during that period. The contemporary atmospheric measurements represent the principal test data for validation of carbon cycle models. The relative importance of enhanced photosynthetic uptake, enhanced respiration, wildfires, and human disturbance to the terrestrial biosphere either today or in a potentially warmer world of higher greenhouse gases in the future cannot yet be predicted with confidence, and may only be determinable from analysis of the detailed global CO_2 record itself.

FOSSIL FUEL CO_2 EMISSIONS AND RESOURCES

Global emissions of CO_2 from fossil fuels increased regularly at a 4.4% annual rate from an estimated release of 1.6 x 10^{15} g C/year in 1950 up to the time of the 1973 oil embargo. Since then the rate of growth has been inconsistent. Total emissions have been relatively stable (~5 x 10^{15} g C) for the past 5 years; annual changes have remained within the estimated 6-10% uncertainties. A variety of factors, including price motivation, has driven energy consumers to conservation, technological innovations, and fuel substitutions (e.g., coal) that require less oil and natural gas. Coal consumption has increased steadily since 1973. The slowed growth rate in emissions has lengthened the time until any specified atmospheric concentration of concern (e.g., twice the year-1800 level) is reached. However, the known recoverable resources of fossil fuels are so vast ($\sim$4000 x 10^{15} g C) that it is highly likely that large quantities will be utilized and that much higher atmospheric CO_2 concentrations will result in time. Refining current estimates of these resources is deemed unlikely to have an appreciable effect on uncertainties in atmospheric CO_2 over the next century.

The fossil emissions time series differentiated on a geographical and seasonal basis, and revised and updated annually, are key reference sources for both emissions and carbon cycle modeling.

UPTAKE OF CO_2 BY THE OCEANS

The oceans, particularly the areas of open ocean, have been the most important sink for anthropogenic CO_2. Knowledge of oceanic processes that determine CO_2 uptake has come mainly from extensive ocean surveys, conducted mostly in the last decade. These surveys have ascertained in varying detail the distribution of chemicals and radionuclides (tracers) that can be used to determine ocean circulation and atmosphere-ocean exchange patterns and chemical and biochemical equilibria needed to estimate CO_2 uptake. These include naturally occurring tracers and transient tracers such as chlorofluorocarbons, tritium, bomb-^{14}C, and excess carbon.

Given the intricacies of ocean circulation, chemistry, and biology, credible estimates of CO_2 uptake can come only from models. The relatively simple, one-dimensional (depth) models initially developed do not take up enough anthropogenic CO_2 to accurately account for known releases and, thus, produce higher concentrations of CO_2 in the atmosphere than was historically the case. Models of intermediate complexity, initial two-dimensional formulations, have generally taken up no more CO_2, and sometimes less, than the simpler models. This has provided further impetus for preliminary developmental work on more elaborate models, which treat chemical and biological processes in three-dimensional representations of ocean circulation. Such models can better utilize existing tracer data for their validation and can begin to incorporate potentially important climate feedback effects on CO_2 uptake. Enhanced carbon storage on continental shelves (0.2 x 10^{15} to 0.8 x 10^{15} g/year), attributed to increasing carbon and nutrient content of river outflows and to carbonate mineral reactions in sediments, could be enhancing contemporary ocean uptake but has not yet been included in models because uncertainties are very large.

Uncertainties about the adequacy of treatment of the oceans in existing models are responsible for a large portion of the uncertainties in predictions of both atmospheric CO_2 increases and climate responses over the period of the next 100 to 200 years. In addition to making fuller use of the expected increase in transient tracer data, more sophisticated models now being formulated should benefit from future direct observations of oceanic carbon uptake and changes in alkalinity (from dissolving calcium carbonate in sediments). The spatial and temporal resolution needed in data to support future modeling is not yet clear but should be clarified as the development of models proceeds. The detailed information gained from oceanic surveys cannot be interpreted without models, and there is little hope of developing more sophisticated models without much more tracer data.

CO_2 EXCHANGE BETWEEN THE ATMOSPHERE AND TERRESTRIAL SYSTEMS

The net release of carbon to the atmosphere from deforestation in 1980 is currently estimated at 0.6 x 10^{15} to 2.6 x 10^{15} g. Longer term calculations indicate a net release of 90 x 10^{15} to 180 x 10^{15} g C between 1800 and 1980. Both the ranges and the high values are smaller than earlier estimates but are still incompatible with ocean model CO_2 uptake. The total mass of organic carbon in the world's terrestrial biota and soils ($\sim$2000 $\pm$400 x 10^{15} g) is so large and heterogeneously distributed that losses at the estimated rate of 0.03-0.1% per year (circa 1980) are currently undetectable. These losses are, therefore, calculated indirectly through models, from the estimated transformation rates of natural ecosystems to human ecosystems (e.g., agricultural lands), on the basis of changes in the relative stocks of carbon in these two types of systems.

The stated uncertainties in these loss estimates result from different assumptions about types of vegetation converted to cropland or pasture, extent of historical degradation of forest carbon stocks, and current carbon stocks and deforestation rates in tropical regions. Some residual variation will remain in the estimates of both current and long-term fluxes of carbon because of the difficulty in documenting past changes in ecosystem carbon stocks and areal extents. Additional uncertainties are contributed by the modeling assumptions currently employed to calculate terrestrial carbon flux estimates. Significant questions exist about the adequacy of the "steady-state" paradigm for undisturbed ecosystems and existing concepts of succession and carbon dynamics in disturbed ecosystems. Climate change could significantly alter the role of the biota in the global carbon cycle, and the biotic flux from deforestation could become secondary to that produced by future global warming.

There is considerable doubt (and speculation) about whether the current terrestrial CO_2 release estimates represent the net flux of carbon between terrestrial systems and the atmosphere or whether there are other sources or sinks from changes in currently undisturbed areas, for example, from climate or CO_2 fertilization effects. Currently, there is no direct evidence for any such changes, and although no consensus exists on estimates of likely future changes, it is recognized that these uncertainties represent major unresolved issues in carbon cycle research.

THE NATURAL CARBON CYCLE

Return of carbon from the atmosphere into the rock cycle during the last 100 million years is currently estimated to be a small fraction of the 0.2 x 10^{15} to 1 x 10^{15} g/year (or more) that has been deposited recently in peats, alluvia/colluvia, and other unconsolidated sediments. Such "subfossil" deposits may have been out of balance for several millennia, and this imbalance may account for a significant part of the mismatch that has emerged from modeling attempts to reconcile trends of carbon in the atmosphere, terrestrial biosphere, and oceans. Uncertainties about the releases of methane and CO_2 from the subfossil pools and the linkages between their respective cycles (even in the natural condition), the effects of varied human manipulations of rivers and their watersheds, and the transience of such phenomena raise very difficult, yet important, questions. Our existing data bases and perspectives are very poor, particularly for phenomena linking inland catchments and river floodplains with estuaries and coastal deltas.

Natural, localized fluctuations in CO_2 exchanges obscure global changes that may already have occurred as a by-product of human intervention. For example, changes in the frequency of wildfires, conditioned by climatic alternations of global or zonal scope (e.g., El Niño/Southern Oscillation events), could have contributed to an important nonfossil fuel complication of the recent atmospheric CO_2 record. But stochastic contributions from fires and changes in natural burning rates through human control also complicate the estimation of both the global biospheric respiration CO_2 source and the net biotic flux with the atmosphere. The role of animals and decomposers in modifying the biospheric respiration flux of over 50 x 10^{15} g C/year remains a basic, unresolved issue—one which must be addressed to understand the impacts of increasing CO_2 and climate change on ecosystems. These examples serve to highlight the fundamental, unresolved problems involved in relating a global synthesis to the local scale at which most carbon cycle measurements or observations are made.

Ultimate reduction of the contemporary imbalance and of carbon cycle model contributions to atmospheric CO_2 prediction errors may not be possible without more basic understanding of fundamental ecosystem patterns and processes (e.g., natural controls on terrestrial carbon storage, role of subfossil carbon pools) and of relationships among ocean CO_2 uptake, climate, and ocean circulation. Lack of relevant field data is the principal obstacle to this understanding. Rethinking of current atmospheric CO_2 reconstructions and of the omission of a land-ocean interface in models is also indicated.

MODELING FUTURE GLOBAL ENERGY AND CO_2 EMISSIONS

The principal uncertainty governing atmospheric CO_2 levels a century from now appears to be the future rate of fossil fuel CO_2 emissions. This, in turn, is related to uncertainties in projected energy use and its determinants: the spectrum of potentially available technologies and fuels as well as a host of difficult-to-predict geopolitical, economic, social, and demographic factors. These currently include the nature of any global response to a climate change only dimly perceived at present. Because all aspects of this complex "human equation" cannot be foreseen, as graphically illustrated by the aftermath of the 1973 oil embargo, much of this uncertainty appears to be irreducible. The modeling of emissions nevertheless provides a necessary tool for treating these uncertainties quantitatively, even if the potential for accurate foresight is slim.

Investigations into uncertainty in patterns of future global energy production and use over the next 50 to 100 years have taken the form of either forecast studies that provide estimates of future CO_2 emissions likely in the absence of explicit control policies or feasibility studies that assess patterns of energy and economic growth consistent with explicit CO_2 emissions constraints. Differences in structure and basic assumptions among current emissions models, however, are such that the key factors in CO_2 releases, while they can be isolated, cannot now be ranked on a quantitative basis.

The rate of global economic growth will be one key factor and will depend heavily on the rate of economic development of currently less-developed countries and the energy demands and choices of energy technologies in that development. End-use energy efficiency improvements also rank high on many studies' lists of important factors. Potential changes in the technologies of both energy end use and supply and the possibilities in interfuel substitutions also must be considered, as such factors add to forecasting difficulties. Continued trends toward use of electricity as a preferred form of end-use energy offer opportunities to meet world needs and ensure economic growth with lower CO_2 emissions, whereas a heavy reliance on coal- or shale-derived synthetic fuels would have the opposite effect. However, future energy supply systems with lower emissions per unit of energy use seem probable as technologies, including nonfossil-based ones, emerge or evolve and as human society awakens to the expected demonstration of measurable CO_2-climate change.

Forecast studies have undergone a dramatic evolution. The dominant techniques of analysis have shifted from time-trend and logistic extrapolations to economic and systems analysis. There has been a concurrent decline in rates of growth of forecasted CO_2 emissions. Prior to 1980, published studies reported annual rates of growth in CO_2 emissions between 2.0 and 4.5% per year. By 1984 the bounds of discussion had shifted to between 0 and 2.0% per year. This trend has occurred concurrently with the introduction of formal techniques of economic analysis; hence a more explicit treatment of key factors. Feasibility studies have consistently concluded that low or declining growth rates in CO_2 emissions are possible if energy conservation and shifts to CO_2-benign modes of production are adopted. Economic costs are generally found to be a small portion of the global sum of gross national products. Although conceptually quite different from forecast studies, the operational distinction between feasibility studies and forecasts is imprecise, and the quantitative differences in projected emissions growth rates between these two classes of studies has diminished. Techniques for describing and analyzing uncertainty have evolved from simple alternative scenario construction to formal Monte Carlo simulations.

Despite an apparent recent convergence in expert opinion about expected future emissions growth rates, a large band of uncertainty remains. The growth rate of global future CO_2 emissions is expected to average approximately 1% per year over the next 75 years. In the absence of explicit policies to control emissions, the 90% confidence bounds are 3.5% per year to −1.0% per year. This excludes a return to the 1950 to 1973 time trend (4.4% per year). Further, low rates of growth (<2.0% per year) in long-term global CO_2 emissions now appear to be possible even without explicit policy intervention. The field of policy analysis has remained largely unexplored.

PREDICTING FUTURE ATMOSPHERIC CO_2 LEVELS

The appearance of high uncertainty in *modeled* fossil fuel emissions and the seemingly high contributions to uncertainty in future atmospheric CO_2 levels are both artificial and potentially misleading. This is because, for a variety of reasons, society will not be free to choose any future path within the current range of potentials. Describing a given emissions scenario as a real possibility in a modeling exercise does not necessarily mean that society could achieve or would want to achieve that scenario, particularly given the implications of CO_2-climate responses for high-CO_2-release scenarios. Decisions and events already have limited the future development of some energy sources; recent trends are toward increased energy conservation and improvements in end-use energy efficiency.

The problems inherent in modeling energy/economic/CO_2 emissions futures on century time scales and, to a lesser extent, current uncertainties in modeling the global carbon cycle make it difficult to accurately project atmospheric CO_2 levels. Despite this, atmospheric CO_2 levels are expected to increase through the year 2075. Although the range of current estimates of the projected increase by 2075 varies from less than 100 ppm to over 1000 ppm above the 1984 level (345 ppm), more likely estimates of this increase are on the order of 150 to 300 ppm. Consequently, doubling of the year-1800-atmospheric CO_2 level before 2025 now seems highly unlikely, and doubling may not even occur within the next century.

Projections of future atmospheric CO_2 levels are based on current understanding of the operations of the carbon cycle and associated geochemical and climatic systems over the past few centuries. It is important to recognize that human activities or even natural phenomena have the potential for altering the dynamics of these systems enough to invalidate *some* current CO_2 projections. Prerequisites for more confidence in the underlying science and assumptions about both balanced and unbalanced conditions of the global carbon system are more widely understood perspectives on the natural biogeochemical cycles of other critical elements (particularly nitrogen and phosphorus, but also oxygen, silicon, and sulfur) and the naturally varying cycles of climate. Because these kinds of cycles interact, studies of them cannot remain as isolated as they typically have been up to now.

Changes in atmospheric CO_2 and climate could be expressed in the form of feedbacks—both positive (unbalancing) and negative (stabilizing)—on the carbon cycle, energy systems, and human ecology. The magnitudes of these feedbacks could be very important. Yet basic understanding is lacking, even in the short term, of several critical processes. These limitations mean that particular outcomes cannot be defined with confidence. Thus, contingency planning for technological and social adjustments will continue to be argued over a range of possibilities that only can be narrowed or elaborated on the basis of new research or insight. Nevertheless, the exploration of a variety of policy options for dealing with the complex issue of global climate change, including the cooperative international development and implementation effort that may be necessary, is still a worthwhile initiative, one that must be undertaken far in advance of demonstrable climatic effects.

TASKS FOR THE FUTURE

No simple guidelines exist for evaluating current uncertainties or for developing the agenda for future inquiries into the workings of the global carbon system. Given the complexity of the CO_2-climate issue in all its varied aspects, uncertainties are to some extent irreducible. Policy decisions, therefore, need to be made intelligently in the face of this uncertainty, both now and in the future. An attempt at a better understanding of the global carbon system seems essential to provide better information for a timely and reasoned response to the effects of CO_2-climate changes. However, projections of CO_2 levels provide only a portion of the atmospheric trace constituent information needed to model future climate changes. Thus, the scope of global biogeochemical research should also be broadened to address the sources and sinks of climatically significant atmospheric constituents other than CO_2.

Significant improvements in the ability to understand and treat (i.e., detect and model) critical processes, including feedbacks, and to attempt a resolution of existing uncertainties are projected to entail a major research effort. Future carbon cycle research should be keyed to removing early, tentative oversimplifications in models as well as to pursuing obvious areas of uncertainty. Without a better perception of the causes for the contemporary imbalance in the global carbon cycle, however, it is not currently feasible to provide a satisfactory ranking of the key sources of uncertainty—important contributions may result from a variety of factors. This ranking is critical to the analysis of policy options, an important precursor to policy formation. In order to attempt to reduce uncertainties over the next decade, the following is required:

1. *Development of a quantitative ranking and evaluation of key determinants of future global energy use and CO_2 emissions using research tools such as historical, engineering, and uncertainty analyses.*

2. *Development of modeling approaches and methods that make more explicit statements of basic biological, chemical, and physical processes responsible for carbon cycling and make better use of available data (particularly for analyzing historical changes in land-use patterns and multiple tracer distributions in the oceans).*

3. *Continuation of detailed reconstructions of land-use changes from primary historical records and from correlates such as population patterns, topography, and so forth, to improve estimates of the terrestrial biospheric CO_2 flux generated during the expansion of farming, forestry, and population over the past 250 years.*

4. *Expansion of process-oriented field research in areas critical to carbon cycle model improvement. Highest priority should be given to the following:*

   - *Completion of planned global synoptic ocean tracer sampling effort (e.g., Transient Tracers in the Ocean Program) in coordination with planned satellite remote-sensing programs (e.g., World Ocean Circulation Experiment) to clarify the relationships among ocean circulation, climate, and geochemical cycles of carbon and critical nutrient elements.*

   - *Continuation of global atmospheric CO_2 monitoring network and its extension to major land biomes in both tropical and high latitudes, coupled with an intensified effort in satellite remote-sensing and ground-support studies to quantify the carbon dynamics of terrestrial ecosystems.*

   - *Intensification of geochemical sampling and modeling (e.g., based on records of elemental and isotopic content in air, ice cores, ocean waters, sediments, and soils) to understand the meaning of atmospheric CO_2 fluctuations, CO_2-climate relationships, and critical links between cycles of carbon and other elements in the recent and distant geologic past. Imbalances over the last 100 to 100,000 years seem in particular need of better quantification as background for modeling and predicting changes in the next century.*

PROJECTING THE CLIMATIC EFFECTS OF INCREASING CARBON DIOXIDE

Concern about the potential climatic effects of the increasing concentration of atmospheric carbon dioxide (CO_2) was first expressed over a century ago, but it was not until the advent of the computer that convincing quantitative projections of the possible effects could be made. Although making up only about 0.03% of the atmosphere's volume, CO_2 plays an important role in maintaining the Earth's moderate climate. Mankind's activities have inadvertently increased the atmospheric concentrations of CO_2 and other gases present in trace amounts (e.g., the CO_2 concentration has increased by about 25% over about the past 100 years), and further substantial increases are projected for the future. Experiments with numerical climate models indicate that increases in the atmospheric concentrations of CO_2 and trace gases, by altering the Earth's heat balance, will produce potentially significant changes in the climate.

The objective of this volume in the State-of-the-Art series of reports is to document what is known about projections of the climatic effects of the increasing CO_2 concentration and to describe the uncertainties and unknowns associated with such projections. This summary follows the same order in which material is presented in the rest of this volume. The changes in the radiation balance caused by the increasing CO_2 concentration (the radiative forcing) are described. The scientific basis for the theoretical models used to make climate projections is discussed, and the latest model results are reviewed. Consideration also is given to the potential climatic effects of perturbations other than increasing CO_2 and to the lessons that past climate changes can teach about what lies ahead. Recommendations are made for research tasks that would contribute toward reducing the uncertainties and improving the projections.

An increase in the atmospheric CO_2 concentration in the absence of an atmospheric response affects the radiation balance of the Earth by reducing the amount of longwave (infrared) radiation that is emitted to space. The CO_2 absorbs radiation that is emitted upward by the Earth's surface and by gases lower and higher in the atmosphere; CO_2 also emits energy upward and downward at a rate that depends on the temperature at the altitude of emission. This trapping of radiation creates temperature profiles that force precipitation-inducing convection and large-scale vertical overturning in order to transport upward a substantial fraction of the solar energy absorbed at the surface. When the concentration of CO_2 increases, the atmosphere absorbs more of the longwave radiation that is emitted upward by the Earth's surface and emits more longwave radiation downward to the surface. Because of the temperature structure of the atmosphere (i.e., temperature decreases with altitude through the troposphere), there is a decrease in the upward emitted radiation that escapes to space when the CO_2 concentration increases. The trapped longwave radiation forces increased convection and acts to warm the atmosphere and surface until the longwave emission to space balances the net incoming solar radiation. This radiation-trapping mechanism is called the *greenhouse* effect. It is a capability implicit in the make-up of all gases that are radiatively active in the longwave regime.

Perturbations other than CO_2 may also affect the climate system. Such climate-perturbing influences include changes in the concentrations of water vapor, trace gases, volcanic aerosols, and other natural and anthropogenic aerosols as well as changes in the solar flux incident at the top of the atmosphere. All of these forcing mechanisms can affect the climate by initially perturbing the Earth's radiation budget. The climate system then tends to respond in such a way as to restore a balance in the net energy budget and in the mass budgets of the various atmospheric constituents. Coupling between physical, chemical, radiative, and dynamical processes distributes the effects of the perturbation throughout the climate system. These perturbations can then result in changes in temperature, precipitation, wind patterns, extent of sea ice, cloudiness, and atmospheric chemical composition.

Because of the complex coupling between physical, chemical, radiative, and dynamical processes in the climate system, it is not possible to derive any simple relationship describing how the climate parameters will change as the composition of the atmosphere is changed. Rather, the system of nonlinear equations that describes the climate system must be solved numerically. The resulting system of equations and solution techniques is called a climate model. Models vary greatly in complexity, depending on their intended application and the level of detail included in describing the various processes and mechanisms. Observational data play an important role in the verification of the climate models and as input to the model calculations. Study of past climates is useful in illustrating the natural variability of the climate on several temporal and spatial scales.

In making projections into the future, it is essential to recognize the distinction between climate and weather. *Weather* describes the state of the global atmosphere-ocean-ice-land system (i.e., the climate system) at one instant in time. Weather can be forecast only a few days in advance. Not only are observations of present conditions inadequate for making accurate, longer term forecasts, but there are also important theoretical limits to how far in advance specific weather conditions can be accurately predicted. The models described in this report cannot forecast changes in the weather, although such models in the future may be able to predict possible changes in the frequency of various weather events.

Climate is the aggregation of the weather, usually expressed in terms of the mean (or average) conditions and variations about this mean, including such statistics as the frequency of rainfall and of such extreme conditions as flood and drought. The normal climate is the collective result of interactions between the atmosphere, oceans, sea and land ice, and the land surface, including, especially, the biosphere. Projecting climate into the future requires predicting the evolution of the mean behavior of the atmosphere, for example, the average winter temperature. Thus, while the weather on a particular January day cannot be forecast, we may be able to predict that a typical January day in the 21st century will be warmer than a typical January day this century or that a typical January 100 years from now will have more mild days than a present January. To some extent, other forcing factors (e.g., a change in solar flux or in the composition of the atmosphere) also determine how future climate will evolve. If the influences of these external factors were to become large, accurate climate projections for the next century would also require better estimates of their influence.

RADIATIVE EFFECTS OF CARBON DIOXIDE AND TRACE GASES

Because convective mixing leads to strong coupling between the upper troposphere (about 5–10 km) and the near surface layer as well as between the atmosphere and the Earth's surface, the change in the net radiative flux at the top of the troposphere (the tropopause) is the appropriate measure to use in calculating changes in temperatures throughout the troposphere and at the surface. A doubling of the CO_2 concentration with no change in atmospheric temperature or water vapor amount would increase the net downward radiative flux at the tropopause by about 4 W m^{-2} averaged hemispherically. These changes would range from nearly 5 W m^{-2} at low latitudes to about 2 W m^{-2} at high latitudes because of the different temperatures and water vapor mixing ratios in these regions. For comparison, the global average net incoming solar radiation at the top of the atmosphere is about 240 W m^{-2}. The maximum change in flux due to a doubled CO_2 concentration would occur in summer and the minimum in winter. Various model calculations of these quantities agree to within about $\pm$10–15%.

Changes in ozone (O_3), water vapor, and trace gas amounts also can have significant effects on the radiation balance and temperature structure of the atmosphere. Absorption of solar radiation by O_3 balances the emission of infrared radiation by CO_2 and creates the relatively warm and stable stratosphere extending upward from the tropopause to about 55 km. The atmospheric water vapor concentrated in the lower troposphere, together with the clouds that form, play the most important greenhouse role of all atmospheric constituents. The atmospheric trace gases that currently have the largest radiative effects (although still relatively small) are methane (CH_4), nitrous oxide (N_2O), and two chlorocarbons ($CFCl_3$ and CF_2Cl_2). Many of the trace gases have band strengths that are greater than the band strength of the 15-μm CO_2 band, but because of their small concentrations, these gases do not have radiative effects as large as that of CO_2. Although the radiative effect of trace gases is currently small, it could increase significantly in the future because the concentrations of many of the gases are projected to increase at relatively high rates as a result of anthropogenic activity. Within the next 50 years, the radiative effect of the trace gases may exceed that of the increasing CO_2 concentration.

Projections of the radiative effects of CO_2 and trace gases into the future are most uncertain because of uncertainties in the projected concentrations of these gases.

Accurate methods exist for computing the radiative effects of CO_2 and other radiatively active gases. Some uncertainty is introduced because of limitations in knowledge of the radiative characteristics of the atmospheric gases, namely the spectral line data and their pressure and temperature dependence. Lack of understanding about the radiative properties of water vapor (especially the absorption continuum and line shape) and simplifications in implementing radiative algorithms in climate models also contribute to the uncertainty in the overall calculations.

PROJECTING THE CLIMATIC RESPONSE TO INCREASING CARBON DIOXIDE

Methods for determining the climatic response to the increasing CO_2 concentration may be either empirical (based on observations) or theoretical (based on numerical models). It is not yet possible to uniquely identify the roles that various causal factors (such as volcanoes, CO_2, and solar variations) have had in affecting climatic variations that have occurred in the past. Consequently, it is not possible to predict the future climate by simply extrapolating trends from the recent past. Attempts have been made to determine the sensitivity of the climate system empirically by examining the changes in radiative fluxes and temperatures that occur during the normal cycle of seasonal change and as a result of small-scale perturbations. These approaches have not proven successful because the time and space domains of these analyses have not been comparable to those of the CO_2 problem.

The only applicable method for projecting future climates is the construction of mathematical models based on the full set of fundamental physical principles governing the climate system. The basic physical laws governing the behavior of many of the components of the climate system are relatively well known, although some aspects of the physics of the various interactive mechanisms and processes serving to link the components together are still uncertain. Some of these interactive processes, including especially changes in the amounts of atmospheric water vapor, cloud cover, and sea ice, have been identified as important feedback processes that can amplify or regulate the responsiveness of the climate system to perturbing influences such as increasing CO_2 and trace gas concentrations. In climate sensitivity studies, lack of knowledge about potential changes of cirrus clouds in low latitudes and stratus clouds in high latitudes contributes most to widening the range of estimates from different models.

Climate models of many types have proven useful in developing an improved understanding of the climate system. The most complex climate models are three-dimensional general circulation models, which represent the global atmosphere, land surface, and oceans. Atmospheric general circulation models are capable of simulating almost all of the observed large-scale features of the climate, and they reproduce the general character of day-to-day variations as well as seasonal changes of the circulation from winter to summer. However, these models do not yet adequately represent the observed regional features that are needed for making the detailed climate projections and assessments of ecological, agricultural, and societal impacts.

The CO_2 concentration is actually increasing slowly; however, it is easier to calculate what might happen if a large increase in the CO_2 concentration were to occur. With climatic feedback processes turned off, different climate models are in close agreement in their prediction of the change in global average surface air temperature for the radiative perturbation caused by a doubling of the CO_2 concentration; the projected temperature increase is in the range of 1.2 to 1.3°C. Global climate models that include feedback processes, however, are not in close agreement; at equilibrium, such models indicate that a doubling of the CO_2 concentration would increase the global average surface air temperature by approximately 1.5 to 4.5°C. The three most recent general circulation model results, which include realistic geography and seasonal dependence, show a CO_2-induced warming of the global average surface air temperature of about 3.5 to 4.2°C and an increase in the global average precipitation rate of about 7 to 11%. The better agreement of the models on the projected global sensitivity is encouraging, but their projections of the regional patterns of such changes vary substantially depending on location.

Model results suggest that equilibrium changes in surface air temperature are likely to be larger in high-latitude regions, near the snow and ice boundaries, than in low-latitude regions. As a result of reductions in the extent of sea ice and snow cover, the predicted zonal mean warming is a maximum in winter and a minimum in summer in the high-latitude regions. This would indicate a significant reduction of the amplitude of the annual cycle of surface air temperature at these latitudes. Regions of positive and negative changes in precipitation rate are simulated, with the largest changes generally occurring between 30°S and 30°N. The change in zonal mean precipitation rate is calculated to be positive in the equatorial region throughout the year and negative in adjacent latitudes for at least part of the year. There are qualitative and quantitative differences among the simulations of the change in precipitation rate, reflecting the uncertainty in these results.

Because society is continually adapting to the current climate, albeit more or less slowly depending on the activity, knowing the expected rate of climate change can be at least as important as knowing what the ultimate change may be. Determining the rate of climate change requires taking proper account not only of the rate at which the atmospheric CO_2 concentration is changing and will change, but also in considering the various climate system mechanisms controlling the rate at which the climate can (and will) change. When perturbations are gradual and persistent, consideration must include the oceans (with their very large heat capacity and slow transport of heat to greater depths), the ice sheets (with their very large heat requirement to be melted), and, in some cases, the biosphere (with its potential to alter surface characteristics and atmospheric composition). The interactive damping factors act to slow the rate of climate change, but they do not change the eventual climatic equilibrium.

In the long term, well-tested, coupled atmosphere-ocean general circulation models may be able to serve as operational tools for simulating the transient climate changes, but these are not now available. A hierarchy of climate models is under development to predict the transient climate response resulting from increases in the CO_2 concentration. Comparison of model results with observed temperature changes in various parts of the globe currently must rely on relatively simplified and approximate approaches in comparison to the models now being developed.

Estimates of the rise in surface air temperature between 1850 and the present due to the increased CO_2 concentration alone range from about 0.5°C to more than 1.0°C, reflecting differences in the sensitivity of the models and differences in the lag time of the ocean response as depicted in the models. As a result, the observed Northern Hemisphere temperature change of about 0.5°C since 1850 cannot yet be used to provide more than approximate guidance on the actual equilibrium sensitivity of the climate to the increasing CO_2 concentration. Time-dependent climate model calculations using standard scenarios of fossil fuel CO_2 emissions indicate that a global warming of approximately 1°C may occur by the year 2000 relative to the year 1850, and an additional warming of a few degrees Celsius may occur over the next century if CO_2 and trace gas emissions continue as projected.

Important uncertainties in model calculations arise from limitations in our understanding of climatic mechanisms and in our ability to represent the various processes in computer models. Representations of clouds, the planetary boundary layer, precipitation, and surface hydrology and of the sensitivity of these processes to changes in climatic parameters contribute most significantly to the uncertainties in the calculations of the potential change in the equilibrium climate.

Uncertainties concerning the climatic sensitivity and the response time of the oceans contribute most significantly to the uncertainties in the calculations of the transient climate change due to the increasing CO_2 concentration.

Uncertainty about the causes of the climatic variations that have been observed over the past 100 years means that the climate record can only provide approximate guidance about the actual equilibrium sensitivity of the climate to the increasing CO_2 concentration.

CLIMATIC EFFECTS OF OTHER PERTURBING FACTORS

The ongoing increase in the CO_2 concentration is not the only factor that scientists believe has already affected or will alter the climate. Geological evidence clearly demonstrates that climate has varied substantially in the past and that natural causes of climate change must be present. On multimillennia time scales, changes in the eccentricity of the Earth's orbit, the seasonal variation of perihelion, and the tilt of its axis are believed to be very important. Some observations also indicate that large natural variations in the CO_2 concentration may have occurred during glacial cycling. On the time scale of centuries, small variations in solar output may play a role; on annual to decadal scales, injections of volcanic aerosols and solar flux variations have probably induced measurable climatic perturbations. In addition, climate variations may arise as a result of nonsteady interactions of the various components of the climate system, for example, as a result of aperiodic overturning of the oceans or long-term instabilities in ice sheet thickness and extent. Such oscillations internal to the climate system add to the background natural variability that may be perturbed by CO_2 and other factors treated as external to the system. Model studies estimate that variations in solar forcing (measured to be about 0.2%) may account for fluctuations in surface air temperature of a few tenths of a degree Celsius. Stratospheric aerosol loadings from major volcanic eruptions may cause a surface cooling of as much as a few tenths of a degree Celsius for periods of one to a few years. These estimates indicate that the climatic effects of solar variations and volcanic aerosols are considerably smaller in magnitude and shorter in duration than the warming projected to result from the increasing CO_2 concentration.

Many gases being injected into the atmosphere as a result of various societal activities can act like CO_2 to trap outgoing infrared radiation and to warm the climate. For example, CH_4 releases that occur as land is cleared, more cattle are raised, and more rice is grown are raising atmospheric concentrations by about 10 to 15% per decade, and emissions of $CFCl_3$ and CF_2Cl_2, which can chemically react to reduce stratospheric ozone, are projected to rise by about 40 to 50% per decade. Trace gases may affect the climate directly by their own radiative perturbation or indirectly by interacting chemically or climatically with species that are radiatively important. Conversely, changes in climate can affect chemical species concentrations by changing temperature-dependent chemical reaction rates. Climate model calculations suggest that, on the time scale of decades, the combined climatic effects of concentration increases of atmospheric N_2O, CH_4, $CFCl_3$, and CF_2Cl_2 and their induced changes in O_3 from climate-chemistry interactions could be as large as those estimated from the expected increase in the CO_2 concentration alone.

Model assessments are affected by uncertainties concerning the feedback processes that involve coupling between atmospheric chemistry, dynamics, and radiation transfer.

Estimates of the future contribution of trace gases to the total projected change depend critically on the projected changes in species concentrations that are used in the calculations. In this regard, a better understanding of the source and sink processes affecting trace gas concentrations and their global budgets is needed to reduce uncertainties in the climate change projections.

THE STUDY OF PAST CLIMATES

The study of climates of the last hundred thousand years can contribute information that may be used to refine scenarios for possible future climates and that can provide independent data for testing the results of global climate models. In addition, such analyses can investigate the causes of past climate change and possibly provide indications of the nature of future climate change. For example, comparisons of warm and cold years in long-term instrumental records have indicated that temperature changes are larger in high latitudes than in low latitudes. This pattern is in general agreement with model simulations of the increasing CO_2 concentration.

Data from the mid-Holocene (about 5000–7000 years ago) indicate that the global mean temperature may have been 1°C warmer than at present, but limited data coverage makes precise determination of the global mean temperature change difficult. The climate during this period was significantly different from today; maps of July temperatures show regions of higher as well as lower temperature in the middle to high latitudes of the Northern Hemisphere. Patterns of precipitation show larger changes than do the temperature patterns, with more precipitation in the tropics and subtropics and less in the midwestern United States.

The analyses show that for most areas, the mean annual surface temperature has been remarkably stable during the past 10,000 years, with variations not exceeding 1 or 2°C. This stability did not extend to precipitation fields, which have exhibited large and extended fluctuations. If increased concentrations of CO_2 and trace gases raise the global mean surface temperature by 1.5°C or more, the resultant average global climatic conditions will be beyond the range of climates that have existed during the historical past and during recent geological times.

The usefulness of past climates for projecting the character of potential CO_2-induced perturbations is affected by uncertainties concerning the causes of past climate variations and the extent to which past warm climates represent the climate conditions that would exist because of a CO_2-induced warming.

SUMMARY OF CLIMATE PROJECTION STUDIES

The atmospheric CO_2 concentration has increased by about 25% since preindustrial times, and continued use of fossil fuels is projected to lead to substantial further increases in the future. Concentrations of trace gases having radiative properties similar to those of CO_2 are also rising. The increasing concentrations of these greenhouse gases will alter atmospheric radiative fluxes and warm the Earth by the very same interactions and processes that enable current concentrations of these gases to make our climate different than that of the Moon. Theoretical projections of the potential future climate changes using computer models whose results have been verified by comparison with the seasonal evolution of the natural atmosphere indicate that a global warming by a few degrees Celsius is possible during the next century. Uncertainties in these theoretical estimates arise in part as a result of the range of CO_2 and trace gas projections, but primarily at this stage they are due to limitations in our understanding and representation of cloud, ocean, cryospheric, and other processes and interactions. As a consequence, different models do not now agree on many of the important regional and seasonal details of expected temperature and precipitation changes, thereby contributing to the difficulty of preparing assessments of ecological, agricultural, and other societal impacts.

Progress in improving the ability to make climatic projections will require continued efforts to improve understanding through computer modeling and analysis and through laboratory observational studies. Detailed model comparisons should help to identify and resolve the causes of differences among models and thereby lead to more accurate projections. By more closely coupling these research efforts with diagnostic studies attempting to reconcile the climatic record of the past 100 years with possible causes of the observed changes and fluctuations, the rate of advance of our knowledge should increase.

Theoretical understanding provides a firm basis for projecting that continuing emissions of CO_2 and trace gases will warm the global climate by a few degrees Celsius during the next century. We are already committed to some of this warming as a result of emissions over the last several decades.

Important uncertainties concerning the regional and seasonal patterns of the temperature and precipitation changes can only be resolved by a broad-based improvement in understanding of climatic processes and mechanisms and in our ability to simulate the climate system.

TASKS FOR THE FUTURE

The overall goal of the CO_2 research program of the U.S. Department of Energy is to provide a stronger scientific and technical basis for projecting the climatic effects of increasing CO_2 concentrations and other perturbations. Such information is essential so that useful assessments of the potential ecological, agricultural, and societal impacts can be made. To achieve the goal of improved climatic projections, improvements need to be made in the models used to estimate the equilibrium climate sensitivity and the time-dependent climate response. Much can be accomplished during the next 10 years. The research needed to improve capabilities for projecting potential future climatic conditions falls into the following five most important areas of activity:

1. *The ability of climate models to simulate observed climate behavior must be more thoroughly investigated.*
   - The results of climate models must be more exhaustively compared with observations of the present climate. Improvement of the ability of climate models to simulate the regional variations of climatic parameters is of special importance.
   - Where possible, climate models should be tested to determine if they can accurately simulate past variations in climate. This requires that the causes of past climate changes be investigated.

2. *Determination of the time rate of climate change requires that oceans and ocean-atmosphere coupling be more accurately treated in climate models.*
   - The dynamics of the upper ocean must be included in climate models so that potential changes in currents, mixed layer depths, and upwelling and bottom water formation rates can be represented.
   - The transport of heat from the mixed layer to deeper levels in the ocean must be included explicitly and realistically in climate models. Field observations will be required to gather the data needed to achieve better understanding of this process.

3. *The adequacy of representations of important atmospheric feedback processes in climate models must be evaluated and improvements added.*
   - The potential for clouds to amplify or moderate climate perturbations must be exhaustively investigated.
   - More accurate treatments of the growth and melting of sea ice and snow cover are required in models so that the high-latitude temperature changes can be accurately projected.

4. *The potential climatic effects of increasing trace gas concentrations require that they be considered as an integral part of the CO_2 climate effects research program.*
   - Atmospheric models capable of treating the radiative, chemical, and climatic interactions of the many trace gases must be developed and tested.
   - Monitoring and laboratory programs are required to provide the data needed to determine the global fluxes, balances, and trends of many trace gases.

5. *Increased effort must be devoted to including consideration of potential changes in climatic variability and the frequency of extreme events in model and analog projections of future climate.*
   - The ability of improved ocean-atmosphere climate models to represent the natural variability of the present climate on regional and larger scales must be documented.
   - Consideration must be given to developing alternative methods for projecting changes in the frequency of rare events. Statistical or analog methods may prove useful.

DETECTING THE CLIMATIC EFFECTS OF INCREASING CARBON DIOXIDE

The potential climatic effects of the increasing atmospheric carbon dioxide (CO_2) concentration, as currently projected by numerical models of the climate system, would constitute a major, extended alteration of the climatic regime that may have far-reaching economic and social consequences. It is, therefore, essential that confirmatory evidence of the projected CO_2-induced climate changes be obtained as soon as possible. The strategy for detecting CO_2-induced climate changes in the observational record consists of the following: (1) determining the climate changes that have occurred, (2) identifying and quantifying the various factors that might have caused or contributed to the observed changes, and (3) isolating those parts of the climate changes that are attributable to the increasing CO_2 concentration, that is, the "CO_2-signal."

The climate research community has devoted a great deal of attention to the problem of isolating and detecting the CO_2-induced climate changes. Recent work has included the assembly and analysis of new geological, historical, and instrumental data. These data are proving useful in developing a better understanding of the sensitivity of the overall climate system to both anthropogenic and natural perturbations, and the data are helpful in verifying and improving present climate models. In turn, the climate modeling studies are helping to identify the climatic variables that appear to be the most promising indicators that climate changes are resulting from the increasing atmospheric CO_2 concentration.

The objective of this volume of the State-of-the-Art series is to document what is known about detecting the CO_2-induced changes in climate and to describe the uncertainties and unknowns associated with this monitoring and analysis effort. This summary follows the order in which material is presented in the rest of this volume. The various approaches for detecting CO_2-induced climate changes are discussed first, followed by a review of applications of these strategies to the various climatic variables that are expected to be changing. Finally, recommendations are presented for research and analysis activities that would contribute to a more definitive identification of the CO_2-induced climate signal.

Climate shows variations on all time scales (monthly, seasonal, annual, decadal, and on up). As a consequence, the appropriate reference climate is not easy to define precisely. A traditional choice is to define climate statistically as the mean state (including the variability) of the atmosphere, ocean, ice, and land surface in a specific region and over a specified time period. Factors such as volcanic emissions, solar variations, and natural fluctuations internal to the climate system may cause variability on time scales of years to decades. On longer time scales, changes in atmospheric composition may also cause climate changes.

Because significant changes in the atmospheric CO_2 concentration started during the second half of the 19th century, it would be desirable to have available a reference climatic data base from prior to that period. Unfortunately, prior to about 1900 the limited accuracy and coverage of observational records of climatic variables pose significant restraints. As a result, a pre-industrial reference climatic state is not available, and the CO_2-induced changes must be sought in data sets that may actually include some early climatic effects, probably relatively small, of rising CO_2 concentrations during the late 19th and early 20th centuries.

Carbon dioxide is not the only atmospheric constituent that may induce climate change. The climatic effects of increasing trace gas concentrations are very likely to be similar to those of the increasing CO_2 concentration, although the magnitude of the changes will depend distinctively on the concentration of each species. Consequently, identification and isolation of the CO_2-induced climate changes from those resulting from other causes are difficult tasks.

THE RADIATIVE SIGNAL OF INCREASING CARBON DIOXIDE

The direct effect of changing CO_2 and trace gas concentrations is alteration of the global radiation balance. This radiative perturbation in turn alters temperatures, which then alter wind fields and other climatic parameters in a continuing sequence. An initial step in isolating CO_2-induced climate changes would, therefore, be identification of the radiative perturbation. To facilitate the detection of these direct changes, the radiative balance of the Earth's atmosphere must be understood. Changes in CO_2 concentration are not expected to result in any significant change in the solar energy absorbed by the atmosphere and Earth's surface. The largest changes are expected to occur in the flux density of longwave (infrared) radiation in the atmosphere. The spectral features (i.e., variations with wavelength) in the longwave flux components are affected by the particular radiative properties of CO_2, water vapor (H_2O), ozone (O_3), and other trace gases, primarily nitrous oxide (N_2O), methane (CH_4), and the chlorocarbons (e.g., $CFCl_3$ and CF_2Cl_2). Changes in the temperature structure of the atmosphere also affect the spectral radiance (distribution of energy over wavelength).

Two viable monitoring approaches for observing this signal are available: to measure the spectral longwave radiance using satellite sensors (looking down from above) or to use ground-based sensors (looking up from below). Both monitoring approaches have their advantages and disadvantages. Satellite sensors could provide global coverage, but calibration of the instruments is more difficult. Ground-based instruments are easily serviced and could be well calibrated, but they cannot easily provide global coverage. In both cases, high-resolution instruments would be required to measure the spectral pattern of change in radiance, which would provide important information about the cause of the change. The relative magnitude of the changes in radiance would be large in certain spectral intervals, but the change in the integrated radiance (called the flux density) would be very small at the top of the atmosphere. Although the radiative signal would be stronger at the Earth's surface than in space, there would be more noise in the signal resulting from the natural variability of temperature and specific humidity in the lower troposphere.

Attempting to measure changes in downward radiance at fixed surface locations does not appear promising in the near future as an approach for detecting CO_2-induced effects on the radiation budget. The primary uncertainty is associated with our limited understanding of the absorption and emission of energy by water vapor. Shifts in the spectral distribution of outgoing radiation at the top of the atmosphere measured by satellites may provide an indication that the CO_2 concentration is increasing, but that is much more easily determined from ground-based sampling. Satellite measurements may also indicate whether radiative fluxes to space are emanating from higher in the atmosphere, as is expected to occur as the CO_2 concentration increases. However, these measurements would not provide detailed information about changes in the radiation budget of the lower atmosphere. Both measurement approaches would benefit from supplemental measurements of the temperature and specific humidity profiles to aid in the interpretation and analysis of the results.

Measurement of changes in downward radiance at fixed surface locations does not appear promising in the near future as a technique for detecting CO_2-induced effects on the radiation budget because natural variations in radiative fluxes are large at the surface and only a very limited areal coverage would be possible.

Shifts in the spectral distribution of the outgoing infrared radiance at the top of the atmosphere measured by satellites may indicate whether radiative fluxes to space are emanating, as expected, from higher in the atmosphere as CO_2 and trace gas concentrations increase. A major source of uncertainty is the lack of understanding about the radiative properties of atmospheric gases, particularly the H_2O absorption continuum, the shape of absorption lines, and the line parameters (and their temperature and pressure dependence). Efforts to reduce instrument noise, provide higher spectral resolution, and provide accurate and stable calibration would contribute to the measurement capabilities.

CLIMATIC DATA BASES

Over the past 5 years, intensive effort has been devoted to improvement of the data bases documenting climatic behavior. The air temperature record over land has, where possible, been extended back from 1880 to 1850 and many more stations have been included. This data set has been carefully scrutinized to identify effects due to changes in the time of recording of temperature, changes in station location, and of urban warming, among other factors. All of these factors can lead to apparent, but false, indications of climate change. A cooperative international effort has made available new records of sea surface temperature and of surface air temperature over the ocean that should greatly improve the spatial representativeness of this record. Records of ocean air temperature and upper atmospheric temperature profiles also have been assembled.

To aid in the analysis and interpretation of temperature changes, data bases also have been developed for volcanic aerosol loading and solar irradiance. The data bases for these quantities vary significantly in the amount and quality of the data, and some of these data sets are inadequate in both respects.

Despite these many efforts to assemble and check the data, there remain limitations in the quality of the data sets. In the case of temperature data, which is the best and most used data set, reliable and standardized instrument techniques were not developed until late in the 19th century. Unfortunately, standardization of measurements did not extend to a policy of a universally adopted observation time so that, even today, significantly different procedures are followed in deriving daily temperature averages. The early data networks were sparse, and, as additional stations were added, they were located primarily over land areas of the Northern Hemisphere. Consequently, data are particularly sparse over large areas of the oceans and the Southern Hemisphere. A significant loss for ocean areas occurred with the reduction in the number of ocean weather stations (located on stationary ships) in the 1970s.

The effects of changes in thermometer type and exposure are considered to be slight, but changes in the technique of measurement of sea surface temperature over the last 100 years have had a significant effect on the readings. Early ship data were taken using the "bucket" method. Over the last 50 years, sea surface temperatures have increasingly been determined using thermometers located in the cooling water intakes. These injection temperatures are estimated to be 0.3 to 0.7°C warmer than the bucket temperatures, which is comparable to the change in temperature estimated to have occurred since the middle of the 19th century as a result of the increasing CO_2 concentration. An important change that can affect a particular station is the growth of towns and cities around the site (the urbanization effect). Increased urbanization around many stations may introduce a warm bias into computed regional temperature trends.

Recent cooperative international efforts have yielded important new data derived from ship records of sea surface temperature and air temperature at sea. Continued expansion of the set of observations of marine air and surface temperatures is essential. Observations at key benchmark stations with long records must be continued.

Data sets documenting changes in volcanic and tropospheric aerosol concentrations and in solar irradiance contain uncertainties that limit their use in interpreting and explaining past climate changes. Continuing and improved monitoring is needed.

ANALYSIS OF CHANGES IN TEMPERATURE

The global mean temperature change is of primary interest because it is the most reliably modeled climatic effect of the increasing CO_2 concentration. Because of limitations in data coverage, there is considerable uncertainty in our knowledge of how global mean temperatures have varied in the past and thus, many workers have used the Northern Hemisphere land-based record as a global proxy. Efforts have been made to fill data-void areas so as to develop hemispheric-mean and global-mean data sets, but such efforts can introduce important uncertainties. In the near future, virtually complete global coverage may be obtainable using satellite data, provided that appropriate calibration techniques can be developed and the satellite and surface records can be related. For the present, however, traditional techniques must suffice.

Five groups have recently published time series of large-scale average surface air temperatures. For land data, the various results are generally highly correlated and show changes of the same magnitude, which is not unexpected because most of the data sources used are common to all analyses. Differences do arise, however, from differences in the number and geographical location of stations employed, from differences in the methods and extent of extrapolation from data-rich to data-poor areas, and from differences in averaging procedures.

Four phases covering the last 130 years can be identified in the time series of Northern Hemisphere temperature: (1) cooling from the mid- to late 1880s, (2) warming from the late 1800s or early 1900s to the 1940s, (3) cooling to the mid-1960s or early 1970s, and (4) warming since the early 1970s. Although the entire globe has shown varying warming and cooling trends, the trends in different regions have tended to differ from each other and from the global and hemispheric mean trends. For example, although there are less vast data for the extensive ocean areas in the Southern Hemisphere, a gradual and more nearly monotonic warming seems to have continued over the period since about 1910. Reconciliation of these different trends is an important problem for detection studies.

Detection of changes in climate that can be unequivocally attributed to the effects of the increasing atmospheric CO_2 concentration involves two steps. The first is a statistical analysis of data directed toward identifying, at a known confidence level, a change in one or more climatic variables. The second is the attribution of at least part of this change to the increasing CO_2 concentration. Statistical attribution is made difficult by the natural variability of the climate, which acts as a noise against which the CO_2, or CO_2 plus trace gas, signal must be detected. In choosing a climatic variable or parameter to monitor for detecting CO_2 effects, it is essential to have both a well-defined signal and a well-defined noise level. The variable that presently best satisfies these criteria is large-scale, area-averaged surface air temperature.

If model results are correct, the rise in the CO_2 concentration since the middle of the 19th century should already have caused an appreciable global surface warming. The amount of the CO_2 warming estimated to have occurred depends on (1) the preindustrial CO_2 concentration, (2) the size of the model-predicted equilibrium temperature increase for a doubling of the CO_2 concentration, and (3) the damping of the response resulting from oceanic thermal inertia effects. Simple energy balance model calculations suggest that temperature changes in response to the increasing CO_2 level may lag a decade to almost a century behind the predicted equilibrium response because of the oceanic effects. Based on land data, the observed increase in global mean surface air temperature since 1850, although apparently oscillatory, is in the range 0.3–0.7°C. (Marine data are in accord with this estimate back to around 1900, but the two data sources diverge prior to this date.) When this temperature range is combined with the probable range of initial CO_2 concentration (260–280 parts per million by volume [ppm]) and the range of ocean lag times mentioned above, then the observations are consistent with an equilibrium temperature increase for a CO_2 doubling in the range of about 1 to 5°C (as calculated using a parameterized ocean-atmosphere model). This result is in broad agreement with the range of climate model estimates of the temperature increase to be expected for a doubling of the CO_2 concentration, which span the range from about 1.5 to 4.5°C.

If more precise values were known for the preindustrial CO_2 concentration and the lag effect of the oceans, a sharper evaluation of climate model results would be possible. For example, if the CO_2 concentration in the mid-1800s was 260 ppm, then the observations would be consistent with a range of equilibrium temperature change from about 1 to 2.5°C, which is not in obvious agreement with the most recent general circulation model results, which project values of about 4°C. Analysis is further complicated by the possible influences that volcanic activity and other forcing factors may have had on the temperature record since 1850. Consequently, although observations of air temperature over the last century are qualitatively in accord with theoretical projections of the climatic effects of the increasing CO_2 concentration, unequivocal identification of a CO_2 signal will require more accurate understanding of the role of the oceans, better model calculations (so that the spatial pattern of projected changes can be sought), and continued improvement of climatically important data bases.

> *Important progress has been made in assembling climatic data bases, although a major gap still exists in coverage over Southern Hemisphere ocean areas. An essential task now is the integration of different data sets and the explanation of apparent discrepancies between them.*
>
> *A major problem in detecting the climatic effects of the changing CO_2 concentration is in explaining the decadal and longer time scale fluctuations in the temperature record, particularly the cooling of Northern Hemisphere land areas that occurrred from about 1940 to 1970. Until these medium time scale fluctuations have been adequately explained or overtaken by further warming, claims regarding detection of CO_2 effects must be viewed with caution.*
>
> *There are major uncertainties in model simulations that make detection efforts on a regional scale difficult at this time. However, such a comparison is needed to gain confidence in the regional scale climate projections made by models for a doubling of CO_2 concentration and as confirmatory evidence of CO_2-induced effects.*

ANALYSIS OF CHANGES IN THE OCEANS

The oceans play an influential role in determining the climate of the Earth, moderating temperature excursions, providing a source of heat and moisture to the atmosphere, and affecting temperature and precipitation patterns over land. Changes in the oceans resulting from the increasing CO_2 concentration may in turn affect the climatic patterns over land. To determine the changes that may already have occurred, data bases of the key ocean variables are needed. The key ocean variables for which some data are available include sea level, temperature, and salinity. The oceans are vast areas, however, and the available data suffer from poor temporal and spatial coverage. There are certain specific locations and small areas where relatively long time series of ocean measurements exist, but for some variables these may not be representative of global changes.

The oceanic variable for which the most representative measurements are available is sea level. A substantial increase in sea level would have a dramatic impact on society because a large fraction of the world's population lives near coastal margins. A sea level rise of more than a meter could have serious ramifications. Although data are sparse, analyses of sea level data completed during the past 5 years indicate that sea level has been rising at a rate of 10–25 cm per century since the early 1900s. A few locations, however, have actually experienced a decline in sea level, contrary to the tendency in many regions. Estimates of the rate of past sea level change can vary by a factor of two simply due to the method of analyzing the same data set, so, narrowing the range of estimates of the global rate of sea level rise will require very careful analysis.

Several processes can cause the sea level to rise. An increase in ocean temperature would lead to an increase of sea level through thermal expansion of the oceans. Thermal expansion of the upper ocean over the past 100 years can explain only a part of the observed change, however. Melting of glacial ice in the polar ice sheets of Antarctica, Greenland, and, particularly, midlatitude mountain glaciers may have contributed significantly to the observed rise, but this is by no means proven. Other possible explanations are highly speculative; a very specific pattern of simultaneous spin-up or spin-down of all of the ocean gyres could result in an apparent increase in sea level in many coastal regions, or a simultaneous subsidence of the continental margins and key mid-ocean islands could be contributing to the observed change.

Globally representative estimates of the temperature change of the upper ocean are somewhat uncertain because of problems with the data sets and analysis techniques. There are only a few studies of subsurface temperature change in the ocean over time scales of decades or longer, and the applicability of these studies to the longer term changes associated with possible CO_2-induced effects is uncertain. These studies provide a valuable starting point for future studies. Long-term, coherent basin-wide changes in the temperature of the ocean at depths below the surface layer are not detectable with the current data set. However, significant local changes have been observed on decadal time scales. These changes may represent a noise that must be successfully filtered out if a larger scale, long-term signal is to be detected.

It is not possible yet to estimate the magnitude of any CO_2-induced changes in the oceans' salinity distribution. Significant long-term changes in salinity may be occurring in a few places in the oceans (for example, in the North Atlantic), but no coherent pattern appears to exist. The problem of noise in the signal appears severe and is unlikely to be ameliorated by current hydrographic sampling programs.

Oceanic data indicate that sea level is rising and that the ocean is warming. Both effects are qualitatively consistent with projected CO_2-induced effects, but a quantitative causal coupling is not yet demonstrated.

The major sources of uncertainty in analyses of ocean variables are the lack of global coverage, the lack of long-term records, and the problem of separating a relatively small signal from noisy data.

ANALYSIS OF CHANGES IN SNOW AND ICE

The principal climatic roles of snow and ice relate to their high reflectivity, the insulating effect of sea ice on the ocean beneath, and the thermal buffering provided by their latent heat. Hence, changes in the extent of snow and ice, their thickness, and albedo are of primary significance in studies of climate changes. Thinning of sea ice allows warming of the winter atmosphere because heat can be more easily conducted from the ocean through the ice to the atmosphere. Reductions in snow and ice cover in response to CO_2-induced warming would tend to amplify the warming by allowing increased surface absorption of solar radiation. This amplification process is termed the ice-albedo feedback effect. The amplified warming would lead to additional melting of snow and ice, thereby making snow cover and sea ice extent potentially sensitive indicators of climate change. On the other hand, ground ice (permafrost), glaciers, and ice sheets are slow to respond to changes in climate.

Detailed records of global snow and ice are generally of much shorter duration than those for most other climate system parameters. Consequently, there are many questions about the variability of these parameters and many uncertainties concerning the representativeness of short-term empirical studies and the modeling of climate-cryosphere (snow and ice) interactions. For example, estimates of the expected CO_2-induced changes of snow cover are currently made by simple interpolation between equilibrium climate states having one and two times the present CO_2 concentration, whereas the time-dependent situation may be nonlinear. The actual changes will depend on regionally and seasonally altered atmospheric circulations and the interaction of the increasing radiative perturbation with the changing seasonal dependence of snow and ice coverage. Detection studies to date have focused on searching for potential CO_2-induced changes in snow cover extent over middle- and high-latitude land masses during the spring, when the thin snow cover may be significantly affected. Because of the large variability in the observational record, however, the CO_2 contribution to changing conditions has not been identified.

Recent studies using satellite data indicate a reduction of sea ice in one sector of the Antarctic Ocean compared with ship observations in the 1930s. Although the change is consistent with the postulated CO_2-induced warming, it is still within the range of natural variability. Modeling studies indicate that reductions in snow cover and sea ice extent should be most evident during the spring and fall because the melting would occur earlier and refreezing would occur later. There is also likely to be a reduction in snow and ice thickness, which may be most evident in late summer and winter when extremes in thickness occur.

A major concern involves the possibility of the collapse of the West Antarctic ice sheet, which is grounded on bedrock below sea level, such that its gradual destruction should lead to a rise in world sea level of 6–7 m over as little as several hundred years. The sensitivity of the West Antarctic ice sheet to a warming is quite uncertain because the effects involve air and ocean temperatures, sea ice extent, and changes in accumulation rate. Estimates of the current mass balance for the whole Antarctic ice cap indicate a net accumulation, but recent iceberg monitoring indicates a rate of iceberg calving that is 3 to 4 times greater than previous estimates, possibly in excess of the net accumulation. Retreat of other icecaps and glaciers could also increase sea level. Mountain glacier recession in midlatitudes could have contributed about half of the observed sea level rise during this century.

Other cryospheric data provide some isolated indications that warming may be occurring. For example, measurements of borehole temperatures in permafrost in northern Alaska imply a warming of about 2°C over the past 100 years.

> *Snow and ice changes that can be directly attributed to the increasing CO_2 concentration are not yet evident, although changes that have occurred are not inconsistent with CO_2 as a cause. Questions about the representativeness of short-term records of cryospheric data at limited geographical locations and the large variability of the data contribute most to the uncertainty in the empirical analyses.*
>
> *Satellite observations have been providing more homogeneous coverage of global snow and ice extent since the early 1970s.*

ANALYSIS OF CHANGES IN PRECIPITATION

Model projections of atmospheric conditions with an increased CO_2 concentration all suggest an increase in the intensity of the evaporation-precipitation cycle. There would be slightly more precipitation on a global average basis, but there could be either an increase or a decrease in precipitation regionally.

To determine whether the increasing concentration of CO_2 is changing the distribution and amount of precipitation, it is necessary to document the past history of the rainfall regime. Although numerous records covering many years exist at many land stations, measurements over the oceans have generally been inadequate. Therefore, estimates of regional and global average values based on past data are highly uncertain. Even though the situation is better for land areas, where it appears feasible to detect regional changes in the record, very important problems must be confronted. For example, instrumentation varies from country to country. Further, individual precipitation systems are relatively small and of short duration, and, accordingly, precipitation records show quite large variabilities on small space scales and short time scales. To generate potentially representative indicators, averaging must be done over large areas and long time frames.

The historical data coverage is not global, so it is not possible to construct a true representation of the global precipitation signal. Further, the data from the land masses do not support the concept of a globally coherent precipitation signal. However, there appears to be a spatially coherent signal in the normalized precipitation anomaly field over a number of continental-scale regions including the United States. The time dependence of these signals is characterized by large decade-to-decade fluctuations on the order of one standard deviation. These variations represent a very large natural noise against which it will be exceedingly difficult to detect a relatively small CO_2-induced signal.

Because CO_2-induced variations may not be uniform (e.g., enhancing tropical and reducing midlatitude precipitation), regional trends and fluctuations must be examined. The recent severe drought in the Sahel has caused numerous investigators to study the past variation of rainfall throughout Africa. The precipitation field over Africa is characterized by large-scale anomaly patterns. The patterns of drought and wet periods persist for years and thus constitute a large background noise. There has been a strong trend toward decreasing rainfall over the continent, which is supported by measurements of the Nile discharge. The cause of this decline in rainfall has not yet been fully determined. These changes are an example of the natural variability on time scales that may obfuscate detection of CO_2 effects and that, on the regional scale, could well be as important as potential CO_2-induced changes, at least over the next few decades.

Limitations in the record of global average precipitation, particularly over the ocean, make near-term identification of any CO_2-induced signal in this record extremely difficult.

When averaged over subcontinental to continental scales, projected CO_2-induced changes in precipitation—even if such changes become better defined as models improve—are likely to be hidden by long-term fluctuations, which are sometimes coherent and perhaps due largely to natural causes.

SUMMARY OF DETECTION STUDIES

The atmospheric CO_2 concentration has increased measurably since the middle of the last century. Northern Hemisphere land temperatures, sea surface temperatures, and sea level have also increased during this period. Model projections of the climatic response to an increased CO_2 concentration indicate that such changes should be expected. The apparent agreement strongly suggests a causal relation.

A critical issue for detection studies is to establish a quantitative relationship that can account for the as-yet unexplained features of the climatic record and is in agreement with model calculations of climatic sensitivity. The non-uniform temporal pattern of the warming on land, particularly the 1940 to 1970 cooling in the Northern Hemisphere, and the conflicting patterns of the changes in the land and ocean records are particularly perplexing, although these difficulties may become less important as the CO_2-induced warming continues to increase over the next few decades. It is particularly important to determine the fraction of the projected equilibrium sensitivity calculated by models that should be evident in current climate records and how this fraction may change with time. This will require improved understanding of oceanic uptake of heat and its transport into the deeper ocean, both theoretically and as portrayed in climate models.

Developing the needed quantitative causal relationship can be accelerated by pursuing signal-to-noise, noise reduction, and multicomponent detection strategies. All three approaches require improved and extended data bases, further analysis, and more accurate modeling studies. Although some studies using each of these approaches have indicated the presence of a CO_2 effect, aspects of these different analyses are not consistent with each other and the derived CO_2 effect is somewhat smaller than suggested by recent climate modeling studies.

Several factors make it impossible to predict precisely when the CO_2-induced changes will be able to be identified with convincing statistical significance. These factors include the uncertainties present in model projections of the induced climate changes, particularly because of uncertainties in representing the oceans, and the possibility that climatic perturbations resulting from changing influences by other causal factors (e.g., volcanic and solar activity, ocean temperatures) could disguise the expected effect of increasing CO_2 and trace gas concentrations. If CO_2 and trace gas concentrations continue to rise as projected and model calculations are essentially correct, the increasing global scale warming should become much more evident over the next few decades. If such changes do not become apparent, our understanding of the uncertainties and completeness of current climate models will require extensive reconsideration.

> ***Trend analysis of long-term records of land and ocean temperatures and sea level are qualitatively consistent with the climate changes projected by modeling studies.***
>
> ***Development of a convincing quantitative cause-effect relationship has been limited by uncertainties in available data sets and in model projections of expected changes, particularly concerning the role of the oceans in delaying the projected climatic warming. Depending on the relative roles of various causal factors, the CO_2 signal should become much more evident over the next few decades.***

TASKS FOR THE FUTURE

The overall goal of the CO_2 research program sponsored by the U.S. Department of Energy is to provide a stronger scientific and technical basis for projecting the climatic effects of the increasing CO_2 and trace gas concentrations. Understanding how key climatic variables have changed since the middle of the 19th century and determining the causes of these changes would contribute greatly to the overall objective of the research program. Validation of the model calculations by comparison with observations is a high-priority task. A two-pronged effort must be pursued: (1) to improve the quality of the data bases and (2) to develop and apply a research and detection strategy that can isolate the CO_2 and trace gas effects from the effects of other forcing factors.

Detection studies require data bases of both the factors that may cause climate changes and of the climatic variables that may be changed. In the State-of-the-Art volume in this series on the carbon cycle, recommendations are presented for improving the record of past CO_2 concentrations. Similar efforts are needed to improve records of changes in solar irradiance, volcanic aerosol loading, and trace gas concentrations over the past 100–150 years and to assure that better records are maintained in the future. Understanding of the climate system and our means of detecting changes also require substantial improvement.

The following research tasks are needed to improve our ability to detect climate change, arranged by the variable being investigated:

1. *Changes in the radiative signal*
   - Accurate measurements of the radiative properties of trace gases (spectral line parameters for the absorption bands and their variation with temperature and pressure) are needed to assess the effect of these gases on the spectral radiance. Also, an effort must be made to validate existing radiative transfer models against laboratory and field measurements.
   - Before proceeding with new monitoring efforts, techniques for extracting meaningful radiative signals from the available radiance data (which have a high noise level due to natural atmospheric variability) must be developed and demonstrated.
2. *Changes in temperature*
   - More extensive data coverage is needed. Satellite data would provide the needed coverage, but the accuracy of temperature retrievals near the Earth's surface is not currently adequate for trend analyses. A considerable effort will be required to determine the correspondence between satellite-derived and surface measurements and to improve calibration and temperature retrieval methods.
   - The causes of the medium (decadal) and longer time scale fluctuations in surface air temperature must be adequately explained.
3. *Changes in the oceans*
   - Sea level stations should be established and sea surface temperature should be better monitored in the Southern Hemisphere oceans. Increased sampling of hydrographic data is needed for selected regions where data records already exist. The sampling program should be sufficiently frequent in time to allow an effective filtering of the high-frequency variability that contributes greatly to the noise level in present data sets.
   - Historical archives of ship observations need to be thoroughly examined to identify possible global-scale changes in various ocean and over-ocean climatic parameters. The apparent disagreement in land and ocean records prior to 1900 needs to be resolved. The cause of the recent freshening of North Atlantic deep water and its relationship to climate and to the bottom water formation rate must be investigated.
   - Better numerical models of the circulation of the oceans, including prediction of the distribution of temperature, salinity, and density, need to be developed. Carefully chosen information from key ocean regions, when put in the dynamical context of such an ocean model, could help identify the data needed to separate possible CO_2-induced effects from other processes that may be causing long-term changes in the oceans.

4. *Changes in the cryosphere*
   - The factors controlling decadal scale fluctuations in sea ice extent and thickness and the stability of pack ice to changes in climate (and vice versa) need to be better understood. Coupled ice-ocean-atmosphere models need to account for the detailed physical processes known to be important so that improved estimates can be made of the changes in sea ice area and thickness expected to occur as the CO_2 concentration increases.
   - Modeling studies, supported by additional field measurements, are needed to ascertain the stability of the West Antarctic ice sheet and adjacent ice shelves to a CO_2 doubling. This question is critical to projecting global sea level on time scales greater than about 100 years.
   - Better observational data must be taken to determine the mass balance and volume changes of the two major ice sheets and a representative coverage of the world's glaciers in order to assess their actual and potential contributions to sea level rise as global temperatures increase.
5. *Changes in precipitation*
   - The precipitation data base must be expanded and homogenized. Although CO_2-induced effects on precipitation are unlikely to be detectable in the next few decades, detailed studies of this data base are needed so that meaningful estimates of regional averages can be developed to compare with model simulations.
   - Possible feedback mechanisms that may amplify the effects of changes in precipitation need to be evaluated. Changes in rainfall, coupled with changes in air temperature, evapotranspiration, and vegetation, for example, may produce a relatively larger effect on runoff and subsequent river flow.
6. *Coupled changes in climatic variables*
   - Improved model calculations are needed that relate, on a regional and seasonal basis, the expected CO_2-induced changes in many climatic variables as a function of time. These changes must be differentiated from the coupled responses that may arise as a result of natural climatic variations and perturbations forced by other causal factors such as volcanic emissions, changes in solar irradiance, and long-term interactions between different components of the climate system.
   - Data sets for individual variables must be improved and compared to assure a continuation of comparable coverage, quality, and length of record.

DIRECT EFFECTS OF INCREASING CARBON DIOXIDE ON VEGETATION

Carbon dioxide (CO_2) is an essential compound for life on this planet. Understanding the direct effects of increasing atmospheric CO_2 concentration on vegetation is an issue independent of all other global CO_2 effects. Plants absorb CO_2 from the atmosphere and become the food supply for other organisms. Because plant growth is limited by the amount of CO_2 in the atmosphere, it is critical to understand how the world's vegetation will respond as the CO_2 concentration of the global atmosphere continues to increase. This volume addresses that issue.

At preindustrial concentrations of approximately 280 parts per million by volume (ppm), atmospheric CO_2 almost certainly was a limiting factor in agricultural productivity and ecological interrelationships. As agricultural technology has been increasing yields throughout this century, atmospheric CO_2 also has been increasing, and by 1985 was approximately 345 ppm. Although there is a considerable range of uncertainty, estimates of growth enhancement range from 0.5 to 2.0% for each 10 ppm increase in atmospheric CO_2. Thus, it is possible that some fraction of the increased agricultural yield that has occurred in this century is due to increased atmospheric CO_2 concentration.

Research has shown, however, that not all species respond to CO_2 in the same manner or magnitude. Plants with high conductance for the diffusion of CO_2 will have greater growth than plants with lower CO_2 conductance. Because many agricultural weeds have high conductance, they could have a comparatively larger growth response to increased CO_2 than some desirable crop species that have lower conductance.

It also has been observed in studies that the food quality of some plant tissues declines as atmospheric CO_2 increases. For example, soybean leaves became carbon rich and nitrogen poor as atmospheric CO_2 was increased without the addition of more soil nitrogen. An insect pest, the soybean looper, feeding on the biochemically changed leaves had to consume more leaf tissue to gain an equal amount of protein nitrogen. Thus, although agricultural productivity may increase in the future, there also may be larger increases of insect feeding rates and weed growth, and this would affect the difficulty and expense of pest control. A full understanding of the many direct and associated secondary effects of CO_2 enrichment is needed for future agricultural productivity to be engineered wisely.

In nonagricultural ecosystems, the direct effects of increasing atmospheric CO_2 are largely unknown. Most experiments to date have been conducted on agricultural species in typical monocultural conditions (with few or no other species cultivated in the same area). In addition, most experiments with non-crop species have been conducted for short periods in inadequately controlled environments. Results obtained in such studies are of little use for the prediction of ecosystem responses to long-term, increasing atmospheric CO_2 concentration. Pertinent studies of ecosystems, the functional ecological units that include both organisms and their abiotic environment, are almost nonexistent, although a few have been initiated within the last 2 years.

In contrast to agricultural systems that are managed to ensure rapid turnover of carbon, the nonmanaged terrestrial biosphere stores large amounts of carbon for long periods of time. Thus, some ecosystems have the potential to sequester a percentage of the increasing atmospheric CO_2. However, a number of secondary responses may occur in conjunction with an increased rate of CO_2 fixation. These include changing interactions among competing plants, altered population of animals, and greater incidence of disease, which may tend to reduce the net carbon content of ecosystems. Thus, the hypothetical carbon-sequestering potential of these systems may not be realized.

This volume summarizes the current knowledge of the direct effects of increasing atmospheric CO_2 on vegetation and the subsequent effects on ecosystems. The indirect effects on plants that might occur from a CO_2-induced climate change (e.g., changes in precipitation or temperature) are only considered in terms of how they modify the direct responses of plants to increasing CO_2 concentration. This executive summary provides an overview of research approaches and technical procedures, discusses our information base, and provides research recommendations where possible.

ANALYTICAL PROCEDURES

Analysis of the direct effects of CO_2 on vegetation has been underway for more than 50 years. Horticulturists realized years ago that adding CO_2 to the air in greenhouses would enhance plant growth. Many commercial greenhouses are routinely CO_2 enriched to accelerate plant development and increase economic yield, and the use of CO_2-enriched greenhouses in research on plant response is still a major technique in use worldwide. The availability of natural sunlight in greenhouses is a desirable feature, but temperature and humidity control in greenhouses is frequently inadequate for research purposes.

Beginning about 1960, environmentally controlled rooms called plant growth chambers were developed, allowing the study of the interaction between CO_2 and other factors: the control and monitoring of temperature, light intensity, relative humidity, air flow, and water and nutrient status of the soil. Although CO_2 control was sometimes employed, sufficient light intensity and routine CO_2 enrichment were not generally available for adequate CO_2 experiments until the late 1970s. Therefore, much of the early data on plant responses to CO_2 enrichment are unreliable.

Because of inadequate environmental control in standard greenhouses and inadequate light intensity of most plant growth chambers, small leaf chambers have been used to enrich part of a plant with CO_2 to determine CO_2 responses. Leaf chambers have great potential for basic research on individual plant physiology and biochemistry. The major weaknessess of this approach are that only part of the plant is CO_2 enriched and that short-term measurements do not adequately describe plant responses associated with anatomical or morphological characteristics that may be CO_2 responsive. Furthermore, it is unknown how well observations using leaf chambers describe whole-canopy processes such as photosynthesis or transpiration.

Phytotrons are large, integrated environmental control facilities that have extensive control and monitoring capabilities. Light, CO_2, water vapor, and soil conditions all can be maintained at realistic levels for long periods. Thus, plants can be germinated and maintained continuously under sufficient environmental control to allow determination of whole-plant, long-term CO_2 response. Both phytotrons and improved plant growth chambers have produced much of the dependable information now available on plant responses to long-term CO_2 enrichment. Only one of the phytotrons in the United States is being used now in CO_2 enrichment research.

Movable greenhouses and controlled environment boxes that may be erected over field crops or intact native ecosystems have been used, but rarely. An exceptional facility of 12 individual chambers with computerized control of CO_2 and other environmental factors is currently in use in permafrost tundra in Alaska. These movable facilities operate in undisturbed field environments under natural light, and provide one of the best approaches available. Large-sized plants, however, require large volume chambers, and environmental control becomes progressively more difficult and expensive as chamber volume increases.

Open top chambers have been used also in field studies of the effects of elevated CO_2 levels. They are essentially plastic enclosures placed around field crops. Air is drawn into a box by fan, enriched with CO_2, and blown through the chamber; air enters near the bottom and flows out the open top. Open top chambers have the great advantage of only partially modifying the field environment; consequently, control of CO_2, temperature, and humidity is not as good as in closed chambers.

The CO_2 enrichment of an uncontained space in a field or ecosystem may be attempted with a free-air-CO_2-enrichment (FACE) facility. In this approach, the CO_2 concentration in the air is raised to desired levels by releasing the gas from a network of pipes. Therefore, the data from these experiments would be free of chamber-induced environmental error. This system has been used for studies of toxic air pollutants (e.g., ozone, sulfur dioxide), but only few experimental attempts have been made with CO_2. Long-term open-air enrichment experiments would provide the best possible validation data for models; however, there are meteorological problems with such research, as well as uncertainties about plant physiological responses to large, short-term variations to CO_2 concentration.

In addition to the actual field experiment approaches, microcomputers and microprocessors are now available that allow more complete and better monitored environmental control than was possible when research was initiated on CO_2 effects.

Requirements for improvements in analytic procedure and, in turn, improvements in the data will necessitate the following:

Improve lighting and CO_2 control in controlled environment growth chambers to be used for CO_2 enrichment research.

Increase the use of existing phytotron facilities for CO_2 enrichment research.

Increase the number of sites where field chambers are in use, and utilize closed or open top chambers as appropriate to meet scientific objectives and practical problems of plant size.

Continue to examine technical aspects of free-air-CO_2-enrichment.

All of the systems described here need to be improved by increasing the use of state-of-the-art computerized control and monitoring systems. This will help improve both the methodology and the data for analysis.

MODELING APPROACHES

Models are needed to integrate various data about crop and ecological systems; to predict plant, crop, and ecosystem response to variable CO_2; and to evaluate interactions such as direct effects of CO_2 and impacts of climate change. It is expected that virtually all physiological processes in plants will be affected as carbohydrate levels change in response to CO_2 enrichment. Furthermore, because plants differ significantly from each other, it is not possible to empirically examine all crops or all native species. Hence, there is a need to model what is known about plant responses and to apply these models to different crop and native species to eventually predict future responses to the changing global environment.

The models that will be the most useful will be mechanistic in nature and capable of extrapolative prediction (CEP). Models that are only capable of simple interpolative prediction (CIP) are inadequate for detailed predictions because empirical information on long-term global CO_2 enrichment is not available. However, semimechanistic CIP models may be useful for first approximations. Because no models have yet been developed completely and validated to accommodate a CO_2 increase as an environmental variable for vegetation response, extrapolative predictions are not possible at this time. The modeling approaches recommended as most effective for predicting direct effects of CO_2 on vegetation include the following:

Develop semimechanistic CIP models of ecosystems and cropping systems that contain those CO_2 responses and environmental interactions for which there is a solid data base. Avoid the development of simple, empirical CIP models that *are based on limited data. These will not be able to predict the response of vegetation to increased CO_2 concentrations and other environmental variables outside the range of data on which they were based.*

Develop CEP models for some of the most important agricultural and native plant species, validate them, use sensitivity analysis to decide how they may be simplified with least loss of accuracy, and aggregate these simpler models into ecosystem and cropping system models.

Explore ways of aggregating CEP single-species models where complexity can be kept at a minimum level.

Introduce stochastic elements in these models to provide a measure of uncertainty in any prediction error.

These modeling approaches require the following data:

Controlled environmental data from growth chambers and phytotrons are needed for building the CEP models. Also needed are more experiments where measurements are made on plants during field releases of CO_2. These will provide the data suitable for developing semimechanistic CIP system models or for validating comprehensive mechanistic CEP models.

In the absence of field-release data, the next best alternative is data from environmentally monitored field enclosures. Only in this way can the environment experienced by all of the plants in the enclosure be known and therefore taken into account when analyzing the data.

A detailed, quantitative description of the above- and belowground environment experienced by plants throughout their life is an essential part of any data set as well as being part of the process needed to modify and improve models for prediction purposes.

The least expensive way of validating the mechanistic models is to first validate them using field data at ambient CO_2 concentration (to elucidate their response to other environmental variables) and then to validate their response to CO_2 using controlled environment data.

AGRICULTURAL SPECIES

Because farmers want to obtain the highest product yield at the highest profit possible, they have selected crop species that can be environmentally or genetically managed. Environmental management includes irrigation, plowing, fertilization, pest control, and planting density. CO_2, the primary source of carbon for terrestrial plants, is a fertilizer. Indiscriminate fertilization is never done by the wise or successful farmer.

However, in the case of global atmospheric CO_2 enrichment, industrialized peoples are indiscriminately fertilizing the entire world. Some crops will presumably increase in economic yield. For example, most species of the 3-carbon photosynthetic pathway show plant growth and productivity increase of 30-50% for a doubling of atmospheric CO_2. Some weed species, however, are known to be more responsive to CO_2 increases than their crop competitors. Therefore, more growth of all plant species is not desirable.

Existing information derived from an extensive survey of 10 important crop species suggests that species (and cultivars of species) differ in their response to CO_2 enrichment. To date, there is not sufficient information to predict which species will benefit most. However, what is known is that some species will respond greatly and some not at all as CO_2 continues to increase. In addition, there is insufficient information about interactions between CO_2 concentration and other environmental factors that affect plant growth. For example, as CO_2 increases in the atmosphere, stomata (variable pores in plant leaves) partially close. Net photosynthesis remains high because of increasing concentration gradient, but water loss through the closing pores declines. The ratio of CO_2 fixed to water vapor lost is termed water-use efficiency. This is one of the most important potential direct effects of increased levels of CO_2 on plants. It could greatly affect the economics of irrigation and extend dry-land agriculture into dryer regions.

Recommendations with respect to agricultural species include the following:

Experimentation in field and controlled environments is needed to elucidate the interactive mechanisms between the environmental factors of temperature, soil, water and nutrient availability, light, gaseous pollutants, soil salinity, and CO_2 concentration. Understanding these relationships is critical to further model development.

Work is needed on the extrapolation of leaf and whole-plant measurements to the prediction of whole-crop response. Plants should be grown in realistic field configurations along with measurements of whole canopy to determine if single-plant measurements can be extrapolated to whole crops.

Experiments should be planned so that crop plants are continuously exposed for their entire growth cycle to a CO_2-enriched atmosphere. Measurements of plants grown for only short periods in high CO_2 environments must be used with great caution. Measurements of CO_2 response made at one stage in a plant's development cycle are not necessarily representative of responses at other stages of growth.

Experiments should be planned and conducted with closer cooperation between experimenters and modelers. Studies should be designed to ensure that results can contribute to the development or validation of plant growth models.

It is impractical to investigate all crop species. Therefore, the following crop species, listed in order of decreasing priority, are recommended for study: wheat, corn, white potato, soybean, rice, sweet potato, sorghum, and cotton.

Mechanistic information on several organ-level responses is particularly missing. Work should be initiated on the following areas: root growth, leaf net photosynthesis rates of plants grown from seed at various CO_2 concentrations, and carbon allocation relationships between phytosynthetic leaves and nonphotosynthetic growing points.

NATIVE SPECIES AND UNMANAGED ECOSYSTEMS

Whereas the biochemical and physiological processes are basically similar in agricultural and native species, these species operate in basically different environments and have been subjected to greatly different selective pressures. Agricultural cultivars have been selected for rapid growth and allocation of the maximum amount of carbon to harvestable organs. The plants are buffered from environmental stresses by irrigation, fertilization, pest control, and so forth, without regard to characteristics that ensure survival and reproduction in the wild. In contrast, native species are subjected to natural selection. Thus, the characteristics that result in desirable crop plants are quite different from those that ensure survival and reproduction of successful native plants. It is possible that native species are now responding genetically to CO_2-induced environmental change and that the adaptive change occurring will accelerate as environmental change accelerates.

Empirical information on native species is scarce. Few long-term ecological studies have been completed and these all have been in controlled environments on isolated plant individuals. More realistic field studies have been initiated but little information is available.

From the scattered information available on native species, speculations have been made about the following:

Representative ecosystems should be studied for sufficient periods of time to determine the long-term equilibrium response to CO_2 enhancement.

For native annuals, initial growth rate may increase but final weight and size may not be affected by increased CO_2. For perennial plants the increases may be accumulated from year to year and carbon may be sequestered in ultimately larger plants. However, in ecologically balanced ecosystems with animals feeding on the plants, disease organisms operating, and plants competing for light, water, and nutrients, it is uncertain whether ecosystem production will increase.

Water-use efficiency (WUE) may be more important in unmanaged ecosystems than it is in agriculture. Plants with the largest net response to the combined effects of water saving and increased growth may outcompete, and thus assume dominance over, less responsive plants. This will be particularly true in semiarid rangelands.

Increased atmospheric CO_2 may induce nutrient impoverishment in the soil of some ecosystems by accumulation of minerals in larger plant bodies. If tissue becomes nutrient poor, decomposition rates may decline, increasing the tendency for minerals to remain organically sequestered. Studies should be initiated on tissue quality, the secondary ecosystem responses or herbivory, and decomposition responses to changing tissue chemistry.

Long-term carbon sequestering has been studied in only one ecosystem: the permafrost tundra of North Slope, Alaska. Without climate change, increasing CO_2 will probably increase carbon sequestering in permafrost areas. Significant warming, however, may change precipitation and ice-melting dynamics, inducing carbon release from the peats as atmospheric CO_2 increases. This would induce a positive feedback, the net result of which has not been examined.

Long-term studies of total ecosystem dynamics are required but technical difficulties are major. This work may have to be restricted to small-stature ecosystems because of financial and technical limitations.

PLANT COMMUNITIES

Differences in response to an elevated CO_2 concentration among the members of an ecological community, interacting through time, are likely to result in changes to the species composition of the community. The composition of communities is a result of differential species response to environmental variables and the resultant competition for limited resources. As CO_2 continues to increase in the future, those species most responsive to the CO_2 increase, interacting with any climate changes that occur, will become dominant. Some species may merely decline in importance whereas others may be eliminated from the community.

From the limited number of studies on plant community responses to increasing atmospheric CO_2, the following can be stated:

Total community biomass will increase. No estimates of the magnitude of increase is possible at this time.

Community composition will change. It is not possible now, however, to predict which species will become dominant and which will become less important.

In communities in which some species have the 4-carbon pathway of photosynthesis and others have the 3-carbon pathway, the 4-carbon species will begin to decline.

Life cycles of most plant species will accelerate. Changing rates of flower, fruit, and seed production may affect coadapted animal pollinators and consumers.

Reproductive potentials will change with concomitant changes in gene frequency.

Further research in community response should be integrated with a modeling effort to help focus research on critical processes.

BIOSPHERIC RESPONSES

To understand the global biospheric response, the individual plant responses need to be evaluated in relation to biospheric processes of the landscape and the global biotic system. One element of this study is to determine if CO_2 enrichment causes detectable growth enhancement and thus increased net carbon uptake and storage by the Earth's vegetation mantle. The purpose is to extend our knowledge of individual plant response to ecosystems, and to determine the extent CO_2 enrichment might affect the Earth's global carbon budget. In this context, the effects of CO_2 enrichment may be expressed in terms of changes of net ecosystem production,

$$NEP = GPP - (R_A + R_H),$$

where the change in carbon budget (NEP) is equal to gross primary production (GPP) minus respiration of autotrophs (R_A) and heterotrophs (R_H). Although a simple concept, it is very difficult to get data for evaluating such relationships of ecosystems, and quantitative estimates of CO_2 effects on global NEP are not now possible. The following types of information are required:

The percentage of each annual increment of atmospheric carbon that can be sequestered in representative ecosystems should be determined.

Carbon pools in representative ecosystems must be better quantified and their resistance to decomposition determined.

The direct effects of increased CO_2 on autotrophic and heterotrophic respiration must be determined.

The interaction of increasing CO_2 concentration with other environmental factors that also might change must be determined.

It is a common practice for simple models of the global carbon system to employ a "biotic growth factor (β)" to represent biospheric growth enhancement from CO_2 enrichment. The "β factor" generally represents a fractional change in NEP in relation to a fractional change in atmospheric CO_2 concentration. Different "β factors" derived have been (1) assumed to be logarithmically proportional to the atmospheric CO_2 increase, (2) estimated from short-term photosynthesis, (3) based on Michaelis-Menten kinetics of plant metabolism, or (4) estimated from annual yield of crop plants. These methods all suggest a positive "β factor," usually ranging from 0.25 to 0.50, but none provides an appropriate, empirically derived expression that represents how fields and forests are responding to CO_2 enrichment. The changing amplitude of the annual atmospheric CO_2 cycle also may be related to an increasing biospheric response, and a detailed analysis of this feature in the Mauna Loa data base yields a "β factor" of 0.4 to 0.5, although the value could be as low as 0.05 if various uncertainties and different assumptions are considered.

Practically all information points to a CO_2 stimulation of the biosphere. Exactly how much cannot be stated now because of inadequate data for representative native species, ecosystems, and biomes. Exactly what happens to carbon fixed by enhanced photosynthesis is also unknown; more information is needed about autotrophic and heterotrophic respiration as well as where the fixed carbon is partitioned in ecosystems. The effects of variable water, light, and other nutrients on the CO_2 enrichment process are also unknown.

TASKS FOR THE FUTURE

In agricultural systems, humans will control adaptation by consciously deciding which cultivars and species are likely to yield the largest harvestable yield and the greatest economic return. In unmanaged ecosystems, natural selection will continue to be the mechanism of biological adaptation to increasing CO_2 levels and any associated climate changes. Adaptation of management practices is a learned behavior. Economic pressures and the rate of application of knowledge gained through research control behavioral adaptation in humans.

For the specific purpose of enhancing the capability of society to respond to the environmental changes associated with atmospheric CO_2 increase, the following recommendations are made:

Screen for overall growth and yield response under high CO_2 levels both with and without environmental stresses and both within and among plant species to identify and select genetically superior individuals. Such research is particularly important for the forest industry because of the small number of breeding cycles that will occur before the onset of the high-CO_2 world. Establish whether screening or other measurements taken on saplings are applicable to mature trees of the same species.

Identify physiological and biochemical characteristics that result in better growth and yield response (i.e., better adaptation) to higher CO_2 concentration. If, for example, specific characteristics such as better translocation into a developing seed can be identified, then breeding or genetic engineering programs could actively attempt to incorporate that characteristic into genetically superior stock. Establish more definitively how growth responses to CO_2 may be affected by light intensity and temperature.

Determine how soil nutrient status affects CO_2 response. More information is also needed about the effects of CO_2 enrichment of nitrogen fixation for various species and conditions. Establish the extent to which greater exudation of carbohydrates and other compounds from roots with high CO_2 levels can stimulate mycorrhizal fungi and other beneficial microorganisms that, in turn, may increase the availability of phosphorus and water to various plant species.

Identify any particular crop-weed combinations that are likely to pose greater problems in the future because of differential responses to increased CO_2 and also to predicted climate changes.

Determine whether plants grown at high CO_2 levels are more vulnerable to attack by insects and diseases. In particular, what effects will a greater *quantity of plant materials that have higher carbon/nitrogen ratios have on host-pest relationships?*

Establish what effect more plant material, but with the high carbon/nitrogen and carbon/phosphorus ratios associated with CO_2 enrichment, will have on decomposer organisms. Similarly, how much will this plant material increase soil organic matter and reduce soil erosion?

The effects of high CO_2 on evapotranspiration and plant water requirements need considerably more attention. The extent to which there is a compensation between decrease in stomatal conductance and increase in leaf area needs investigation for many species. Establishing the effects of increased CO_2 on canopy development and leaf temperature and how these relate to evapotranspiration is also necessary.

More information is also needed about the effects of high CO_2 and partial stomatal closure on internal plant water status. To what extent can high CO_2 levels ameliorate plant water stress and maintain high productivity under dry conditions? Similarly, to what extent can high CO_2 levels counteract the effects of salinity and air pollutants?

Hydrologic modeling research also is needed to account for changes in precipitation, runoff, and evapotranspiration on streamflow in the future high-CO_2 world. The effects of decreased stomatal conductance and increased leaf area on evapotranspiration as well as the effects of increased stand density on runoff must be understood.

Systems-level models and analytical approaches need to be developed for predicting agricultural and ecological responses to both CO_2 enrichment and climate change. In particular, process-type models are needed that account for unique plant and system-level properties. The models should be generically applicable to different situations and should also be capable of analyzing alternative resource management practices.

CHARACTERIZATION OF INFORMATION REQUIREMENTS FOR STUDIES OF CO_2 EFFECTS: WATER RESOURCES, AGRICULTURE, FISHERIES, FORESTS, AND HUMAN HEALTH

OBJECTIVE OF THE INDIRECT EFFECTS STUDY

The goal of the Carbon Dioxide Research Program is to produce a balanced assessment of the Carbon Dioxide (CO_2) question as the scientific foundation for evaluating future energy policy issues. Efforts toward this goal include research on (1) carbon cycle (CO_2 exchange between the world and its atmosphere), (2) the potential for climate change resulting from increased CO_2, (3) the extent of vegetation response to increased CO_2, and (4) the possible effects on other issues that result from climate and vegetation change. In the Department of Energy's Carbon Dioxide Research Program, climate change and vegetation response are termed direct effects of CO_2. Changes that result from climate and vegetation change are termed indirect effects and are the topic of this report.

There are still many uncertainties about the carbon cycle and the direct effects of CO_2. Because of these uncertainties, it is currently not feasible to do an impact assessment of the indirect effects of CO_2. This study seeks to define and characterize the information and data required for quantifying indirect effects, including the requirements from direct effects research and from within the fields in which indirect effects may occur. The purpose of this is twofold: (1) to inform the direct effects researchers of the specific needs for quantifying indirect effects and (2) to determine whether additional data are required and improvements needed in research techniques (for example, data collecting methods and modeling) within the fields where indirect effects may occur. These improvements will be necessary for the efficient use of the information that will evolve from direct effects research.

APPROACH

Based on indications from earlier literature and the relationships of various issues to climate and vegetation, the following six fields were selected for study: sea level, water resources, agriculture, fisheries, forests, and human health. All these fields are pertinent to human welfare and potentially can be influenced by climate and vegetation change. Sea level was studied and reported separately and will not be addressed in this report.

Literature searches and, in some instances, case studies were used to characterize and define the relationships between these fields and climate factors and the growth and extent of vegetation cover. Data needed from direct effects research were determined; requirements for data and research within the fields of study, needed for efficient use of information as it evolves from direct effects research, were defined.

Because of restrictions of time and resources this study necessarily was limited in scope. These limits did not prohibit the identification of many of the most critical data and research needs; however, indepth examination of the full extent of the research and effort necessary to supply the needs was not achieved.

RELATIONSHIP OF INDIRECT EFFECTS TO OTHER CO_2 RESEARCH PROGRAMS

Carbon Cycle

The extent and rate of climate change and vegetation response will depend on the extent and rate of CO_2 change in the atmosphere. Thus, information on the carbon cycle is basic to determining all other effects of CO_2. Among the topics studied, agriculture, forests, and fisheries appear to have the potential to be affected directly by CO_2. The direct response of agriculture and forests to CO_2 is being studied separately in the vegetation response research program. The concentration of dissolved CO_2 in sea water, which will be in equilibrium with CO_2 in the atmosphere, may affect the phytoplankton (aquatic plants at the base of the fishery food chain) and thus fisheries in general. In addition, an increase of dissolved CO_2 in sea water may change the pH (acidity) and thus other aspects of ocean chemistry.

Although progress is being made in research on the carbon cycle, there are still gaps in information, particularly about the sources and sinks of CO_2. These currently preclude prediction, over long periods of time, of the rate of increase and the eventual maximum concentration of atmospheric CO_2.

Climate Change

Predictions of global temperature change range from 1.5°–4.5°C. Temperature change will affect climate variables, such as precipitation and humidity. Thus, all of the five fields studied will be affected if there is appreciable climate change with consequent changes in regional and seasonal weather.

Regional and Seasonal Changes. The term regional, as used here, may denote quite different areal magnitudes, depending on the effect being researched and the topography of the region in question. For example, (1) water resource drainage basins may be very small or, in the case of large rivers, may be as large as thousands of km^2; (2) some specialty crops are grown in small regions, whereas major grain belts cover thousands of km^2; and (3) the spawning areas of some fishery species may be as small as a single bay or river, but some adult species range over entire oceans. The seasonal information required for one study also may differ from that required for other studies. Changes in the timing of spring or fall frosts or of precipitation, for example, may affect one crop differently than another, depending on where each is in its growth or harvest cycle when these meteorological events occur.

Regional and seasonal changes in climate and weather are important for each of the fields studied. Changes in yearly global means, although they give a general indication of the direction of changes, are not adequate for determining indirect effects during particular seasons and, particularly, in regions where change may be modified by factors such as topography, nearness to oceans, and distance from the poles. For example, crop and forest species need specific amounts and timing of heat and precipitation, and these differ from one species to another; fisheries are individually adapted to the seasonal ocean temperature of their current environment; humans, apparently, have some physiological adaptability to the climate in which they have lived for long periods; pests, pathogens, and parasites occur in regions where seasonal climate and weather conditions are conducive to their survival. Should CO_2-induced regional and seasonal changes remove environmental stress on plants, humans, pests, pathogens, or parasites these entities will be more likely to survive and thrive; should stress from climate and weather factors increase, the opposite will occur.

Extent of Climate Change. The extent of temperature change needs to be defined more precisely. Temperature will influence water resources by affecting evaporation from surface water supplies and from soil surfaces; temperature influences agriculture by the degree of warmth and the length of warm periods, which determine the growth periods and growth rates of crops. Unseasonal or exceptionally hot or cold periods may kill plants and may affect the health of farm animals. Fisheries are generally adapted to the temperature of their regional environment. Changes in ocean properties (temperature, pH, salinity) can impact fisheries and their food chains. Their predators and their competitors may become unbalanced, and the fisheries may decline or migrate. Forest growth and survival may be affected by extreme temperatures. Human health may be affected by changes in temperature because mortality from diseases such as heart, respiratory, and cerebrovascular is higher with extreme temperatures, and organisms (bacteria, viruses, parasites and their hosts, and pollen) responsible for diseases are frequently extremely sensitive to temperature; effects on water resources, agriculture, and fisheries may, in turn, affect human health.

Precipitation patterns may change as a result of temperature change. Knowledge of the extent of this change will be needed to determine indirect effects. Changes in precipitation patterns will affect (1) water resources by affecting the rate at which they are replenished; (2) agricultural crops because they need specific amounts of moisture at critical points in the growth cycles; (3) fisheries, especially during immature life stages, by the extent of runoff into bays and estuaries; (4) forests, which need soil moisture at certain seasons for growth and survival; (5) vectors of human disease, which frequently need aquatic environments replenished by precipitation.

Knowledge of the extent of change in other climate and weather variables also is needed. Humidity, for example, modifies the effect of temperature on water resources, plants, pests, and humans; storms can damage crops, parts of fishery life cycles, forests, and other plant species; wind (air movement) will modify the effect of temperature.

Rate of Climate Change. The rate of climate change will affect all the fields studied. It will affect the rate at which (1) indirect effects take place, (2) humans and animals acclimatize, and (3) technological measures (e.g., building new reservoirs, genetic improvement of crops or animal species, new or accelerated disease and pest control technology) need to be adopted.

Variability of Climate and Weather. To determine the indirect effects, it will be very important to have information about changes in the variability of climate and weather, that is, whether fluctuations around the mean value for a particular variable become larger or smaller and whether extreme fluctuations occur more or less frequently than in the current climate. For example, should temperature variability decrease during the growing season, even though the mean temperature has increased, agricultural adaptation would be accomplished more easily than if variability increased.

Similarly, humans, agricultural plants and animals, fisheries, and forest species are expected to be very susceptible to abrupt or extreme changes in weather (heat waves, excessively cold periods) and to extreme weather events (storms, floods, and hurricanes). Pests, pathogens, and parasites also will be affected by extreme weather changes; some may not survive these changes, whereas others may find new opportunities to invade their hosts, such as in wind-damaged forests. If these events occur more often, or with more severity than in the current climate, the effects would be more damaging than if they occur less often.

Although current climate models predict global changes in climate, they do not yet agree on the extent of the changes and are not yet capable of predicting the regional and seasonal information necessary for determining the extent of indirect effects.

Vegetation Response

Plants absorb CO_2 from the atmosphere, and increased CO_2 in growth chambers has been shown to enhance growth and water-use efficiency of some plant species. However, much research still is needed to determine issues such as whether (1) the nutrient value of specific crops is changed, (2) the effects are limited by the availability of other nutrients, (3) there will be changes in insect feeding rates and weed growth, and (4) the nonagricultural ecosystems will be affected. These changes, in response to increases in atmospheric CO_2, will be taking place at the same time as the effects of climate change on plants. These two influences on plants will probably be synergistic in their actions. Thus, it is necessary to know to what extent vegetation response to CO_2 may moderate the effects of climate change on plants to predict the effects on crops, vegetation cover in water resource basins, as well as other natural vegetation, forests, and aquatic plants (especially in relation to fishery food chains).

The extent of the CO_2-induced vegetation response of important crop, forest, native, and aquatic plant species is currently uncertain, as are the interactive effects of CO_2-induced climate change and vegetation response on vegetation.

RESEARCH NEEDS WITHIN THE TOPICS STUDIED

In addition to the information needed from CO_2 research programs, there are unknowns and uncertainties in the information within the fields studied, which will require research or development of new or modification of current techniques, for example, methods for obtaining pertinent data or improving or developing new models. Some illustrations follow.

Water Resources

Watershed models need (1) more accurate characterization of the effects of climate change on the hydrologic systems of individual drainage basins, (2) inclusion of the effects of changes in vegetation type and the extent of vegetation cover, and (3) the ability to determine the effects of changes in land-use patterns on hydrologic response. Methods are needed for predicting (1) long-term changes in land-use patterns, (2) the magnitude and timing of sectorial demands for water, (3) the rate of adoption of technological innovations designed to ameliorate the impacts associated with specific water resource issues, and (4) the effects of changes in the legal and institutional base for water resource allocation and in management practices.

Agriculture

Some requirements are (1) the development of economic models, which will evaluate the consequences of changes in farm policy and farm markets and integrate these with CO_2-induced changes, (2) field and simulation studies of water utilization and the economic return from irrigation, (3) studies on the feasibility and impacts of migration of cropping zones, including the effects on crops of soils and their erosivity in potential new zones, (4) genetic research to develop stress resistant cultivars and to broaden the genetic base of food crops and to develop new breeds of agricultural animals that can adapt to a changed climate, and (5) a greater understanding and quantification of climate and weather influence on agricultural pest life cycles and on the natural enemies of the pests.

Economic factors also may interact with CO_2-induced effects. The cost of such items as irrigation, fertilizer, and pest control and the economic return from particular crops will interact with CO_2-induced effects to determine, for example, whether farmers will continue to raise specific crops in particular areas.

Fisheries

Additional field information and technology improvements in fisheries research are required. These include (1) surmounting the difficulties encountered in locating and enumerating the early life stages of fishery species and in correlating the abundance of adult fish with oceanic conditions (related to climatic conditions) prevailing at the early life stages; (2) acquiring more knowledge of fishery-ocean interactions and biological relationships (between food chains, predators, competitors) to make quantitative projections of the effects of climate change and to develop simulation models; (3) developing the capability of models to include several individual effects (e.g., turbulence, salinity, and ice) simultaneously over broad spatial and temporal scales, while still adequately representing the small-scale variability that is biologically significant; (4) developing methods for assessing the effects of pH change (due to dissolved CO_2) on ocean chemistry; and (5) assessing the effects of dissolved CO_2 on primary productivity.

National and international regulations of fishery catches may interact with CO_2-induced effects; that is, should there be a combination of overfishing and detrimental CO_2-induced effects, a particular fishery may decline more rapidly than would be the case otherwise. Conversely, if fishery catches are well monitored and halted, should there appear to be a decline in a particular fishery, this may partly offset a CO_2-induced, detrimental effect by allowing the fishery to recover.

Forests

More research regarding climate change and forests is needed. This includes (1) developing modeling approaches that represent both decadal and millennial transient responses of vegetation; (2) obtaining field data required to support, extend, and improve existing models; (3) developing methods for predicting the effects on forests of changes in land use and forestry management, which may occur concurrently with CO_2 increase; (4) identifying the environmental forces causing present dieback in forests; (5) investigating the possibility that warming of the Earth may lead to dieback of some of the dominant tree species and may result in boreal trees being replaced by deciduous species during several hundreds of years; and (6) investigating the effects of climate change on forest pests and soil biota.

Economic factors (interest rates, demands for forest products) may interact with CO_2-induced effects to determine the outcome for specific commercial forest stands because these factors may determine whether these forest stands are abandoned or reseeded or replanted.

Human Health

Some of the relationships of human health to climate need elucidating. These include (1) obtaining more definitive information on the relationships between meteorological variables and the onset, progression, and outcome of heart, cerebrovascular, and some respiratory diseases; (2) determining whether the warming of winters in colder climates might diminish early death rates from organic diseases and, conversely, whether increasing summer temperatures in warmer climates might increase early deaths from these diseases; (3) obtaining better definitions of the specific environmental conditions that support the survival and spread of some disease-causing and disease-transmitting organisms; (4) increasing knowledge about the interaction of climate (which may act directly on humans and disease vectors) and nutrition (which may be affected by both CO_2-induced climate change and vegetation response) to determine whether there might be long-term regional change in disease susceptibility or disease outcome; and (5) investigating the possibility that effective application of technological advances (parasite eradication, improved health care, new disease treatments) could offset or prevent the potential, detrimental health effects of CO_2 build-up.

Within the five topics studied here, there are gaps in the knowledge and technology required to quantify indirect effects. Some requirements are: (1) collection and analysis of available data relating climate and vegetation parameters to issues, (2) collection of new data where needed to fill gaps in data bases, (3) reorientation of some current research to address issues raised by CO_2, (4) improvement of methods for data collection and analysis (e.g. modeling), (5) studies of the efficiency of adaptive processes and measures, (6) studies of factors that may modify the consequences of indirect effects.

POTENTIAL MODIFYING FACTORS

Many factors may modify the eventual consequences of the indirect effects of increasing atmospheric CO_2. Although this study is not oriented explicitly to search for, or evaluate, these factors, some are listed here to point out the possibility that some of the consequences may be modulated. However, they have not been evaluated in this study for their scientific, technological, or economic feasibility. These factors include (1) limited physiological acclimation by humans and animals; (2) changes in clothing and shelter to counteract extreme heat; (3) genetic development of strains of plants and animals more resistant to climate change; (4) technological solutions for potential problems in water resources, agriculture, forestry, and fisheries; (5) increased efficiency of pest, parasite, and pathogen control; (6) the possibility of planned migration of crops to regions with more suitable climates; (7) the possibility of migration of fisheries and wild animals to more suitable environments; (8) changes in economics, such as interest rates, costs of water and fertilizer, and changes in the return from specific crops; (9) changes in land use; and (10) changes in local, national, and international regulations, such as those on water allocation, import and export of commodities, and limits on fishery catches.

The extent to which modifying factors will influence the consequences of indirect effects of increasing atmospheric CO_2 (either beneficially or detrimentally), is uncertain.

DATA NEEDS AND TASKS FOR THE FUTURE

There are many uncertainties about the indirect effects of increased CO_2. To clarify most of these, reliable information about the direct effects of CO_2 is critically needed. However, there also are some uncertainties about the manner in which climate and vegetation change (if known) would affect the fields studied and, there is a need for improved techniques for data collecting, modeling, and so forth. The following information and measures are needed with respect to the topics studied:

1. The rate of increase of atmospheric CO_2 and its eventual concentration.
2. The regional and seasonal extent of change of climate and the weather elements, the rate of these changes, and the changes in their variability.
3. Regional and seasonal vegetation responses of plant species that are important to water resources, agriculture, forests, and fisheries.
4. The effects on plants of the interactions of CO_2-induced climate change and vegetation response.

5. The development of new or the analysis of existing data bases and improvement of research techniques within the fields studied, needed to predict the indirect effects of CO_2, as information evolves from direct effects research.
6. Studies on the potential of adaptive measures, such as genetic development of crops adapted to new climates or construction of new reservoirs, to influence the extent of indirect effects of increased atmospheric CO_2.
7. Model development for predicting the potential for modification of the consequences of indirect effects by concurrent factors such as economic changes, changes in land use, and changes in local, national, and international regulations.

GLACIERS, ICE SHEETS, AND SEA LEVEL: EFFECT OF A CO_2-INDUCED CLIMATIC CHANGE

The rising concentration of CO_2 and other greenhouse gases in the atmosphere is likely to produce a warmer climate in the future. One consequence of this might be an ensuing rise in sea level caused by the melting of ice on land and by volume expansion of ocean water. Uncertainties occur in all aspects of the problem of attempting to estimate sea-level rise.

In order to define our current knowledge of how much water is exchanged between land and sea, the Committee on Glaciology of the Polar Research Board convened a Workshop on the Interactions between Land Ice and the Oceans, in Seattle, Washington, September 13–15, 1984. This workshop builds on a workshop held in 1983 on the Environment of West Antarctica: Potential CO_2-Induced Changes. The Department of Energy supported both workshops. The focus of the 1984 Workshop was on defining what is known and what needs to be known about the contribution of ice melt to sea level at the present (defined as the past 100 years) and what that contribution is likely to be in the future (defined as the next 100 years) assuming that the climate will change significantly. Oceanographic, climatologic, geophysical, and glaciologic evidence was examined by invited experts. This report summarizes the consensus of the Workshop, mentions areas of uncertainty, and makes recommendations for research needed to reduce these uncertainties. The body of the report is followed by 23 signed attachments prepared by the invited experts.

> The consensus of the Workshop is that sea level is rising, but the rate of rise is uncertain by a factor of 2; wastage of mountain glaciers and small ice caps contributes to this rise; probably very little if any sea-level change is caused by wastage of the Greenland Ice Sheet; and the Antarctic Ice Sheet is most likely growing, taking water out of the sea. The rate of change of mass of the ocean cannot be distinguished from zero. Whether the present rise in sea level can be adequately accounted for by just thermal expansion of ocean water is an open question. Future projections suggest that, in spite of increased precipitation, wastage of small glaciers and the Greenland Ice Sheet will add mass to the ocean; the resulting sea-level rise due to this cause likely will be a few tenths of a meter by the year 2100. The sea-level rise due to changes in Antarctica is more uncertain; most likely it will be small, but a rise of an appreciable fraction of a meter by 2100 due to increased discharge of land ice to the sea is not beyond the realm of possibility.

Since the turn of the century, measurements of relative sea level suggest a global average rise of 1 to 3 mm/yr; however, the data coverage from the central ocean regions and the southern hemisphere is poor, and tectonic and isostatic disequilibrium effects have not been removed from most records. A preliminary calculation of the continuing adjustment of the Earth to the removal of the Laurentide and Fennoscandian ice sheets results in a corrected value of a little more than 1 mm/yr along the eastern U.S. coast. These corrected values still show considerable spatial variations of unknown cause. Ocean surface temperature appears to have risen by 0.6 ± 0.3°C since the turn of the century, but this result may be biased because of changing instrumentation and observation techniques. Those models that are currently used for computation of the increase in ocean volume due to thermal expansion generally do not incorporate the essential physics of deep-water formation and movement. The few observational data on changes of ocean temperature, salinity, and density structure during the last several decades show no statistically significant change except in local areas; a longer record is needed for firm conclusions. Atlantic water north of 50°N has slightly freshened since 1972, but this may be a temporary condition.

The glaciers and small ice caps of the world, excluding the ice sheets of Antarctica and Greenland, have, in general, been shrinking during the past 100 years (Table 1). However, the data set is temporally and spatially sparse. Most of the glacier wastage that contributes to sea-level rise is thought to be derived from the mountain ranges bordering the Gulf of Alaska, Central Asia, and the Patagonian ice caps, but these are areas with few observations. In some regions, even the area of glacier ice is poorly known.

Table 1. Estimated Mass Balance of Glaciers and Ice Sheets at the Present Time[a]

Ice Mass	Average Mass Balance (water equiv.) (m/yr)	Effect on Sea Level (mm/yr)	Report Section
Glaciers & small ice caps	−1.2 ± 0.7	+0.5 ± 0.3	3.3
Greenland Ice Sheet	0.02 ± 0.08	−0.1 ± 0.4	3.4
Antarctic Ice Sheet	0.02 ± 0.02	−0.6 ± 0.6	3.5

[a]*Note:* error limits represent approximate bounds of estimation and cannot be defined statistically.

Observations of present elevation changes of the Greenland Ice Sheet surface indicate thinning of the marginal zones and thickening of the central area. Accumulation rates are reasonably well known; ablation rates and their gradient with altitude are known only for a few sites in West Greenland; iceberg discharge has been measured for some outlet glaciers in West Greenland, and few estimates have been made along other coasts. Thus it is currently not possible to estimate reliably the exchange of mass between the Greenland Ice Sheet and the oceans, but most estimates suggest that gains and losses are about equal.

The present-day net balance of the Antarctic Ice Sheet is still not known precisely, but estimates have been improved over the past decade and most estimates suggest growth. The biggest uncertainties are in iceberg discharge, accumulation amounts in some regions, and rates of melting below the major ice shelves; also, few data exist on changes of the margin. The physics of the dynamic response of the ice sheets to variations in climate is known in general terms, but some processes are not well understood or have not yet been incorporated fully in numerical models. Major gaps in understanding concern basal sliding, the coupling of ice streams with the ice sheets in which they are embedded, and what determines the position of the seaward (calving) face of ice shelves. The present-day true polar wander and the nontidal acceleration of the Earth's rotation can be reproduced using modern models of the Earth's structure combined with a scenario for the loss of the Pleistocene ice sheets, without any need to assume present-day changes of ice-sheet volume, suggesting approximately zero mass balance for both the Antarctic and Greenland Ice Sheets.

In order to predict future changes in land ice due to a perturbed climate, climate models are required. Steady-state (asymptotic) models indicate, for a doubling of CO_2, a predicted average temperature rise of 2 to 4°C or possibly more. The global temperature rise is probably amplified at high latitudes. The major uncertainties result from the difficulty of parameterizing sea ice and predicting the effect of clouds on the perturbed climate. The physical basis for certain features predicted by the models is still not clear. Runoff, as opposed to melting, at the margins of the two existing ice sheets is not yet properly modeled. Predictions made by steady-state models incorporating a CO_{-2}-perturbed climate show similarities in the global-scale distribution of climate variables, but the agreement is poor in regard to regional, longitudinal variations and in the higher latitudes and in the anticipated changes in precipitation. The time-dependent evolution of climate, driven by a changing CO_2 concentration, is extremely difficult to model, and many aspects are poorly understood.

Energy-balance models, as well as simple statistical, empirical models, exist that can be used to estimate the additional wastage (or growth) of glaciers and small ice caps in response to a perturbed climate. However, insufficient data exist to calibrate these models in most regions, the models are not easily linked to general circulation models, and glaciers in regions of monsoonal circulation are difficult to model. Mass-balance histories are often dominated by rare years of extremely negative balances, a further difficulty. Complete removal of the small glaciers of the world would cause a sea-level rise of 0.3 to 0.6 m.

Several ways exist for estimating the response of the ice sheets to a CO_2-perturbed climate. Estimates of the contribution to sea-level rise from the Greenland Ice Sheet are severely limited by lack of present-day data, as well as by lack of understanding of how the balance processes relate to large-scale climatic processes, how the infiltration/refreezing regimen would react to an increase in meltwater availability, and how iceberg calving would be affected.

Knowledge of ocean circulation near and under Antarctic ice shelves is limited. If a doubling of CO_2 in the atmosphere were to cause an increase in the temperature of circumpolar deep water of about 0.5°C, then a proportional increase might occur in the temperature of "warm" inflows onto the continental shelf. If the shelf circulation were to change so that circumpolar deep water intruded beaneath all the ice shelves as freely as it does today beneath the George VI Ice Shelf, then the average ice-shelf melt might be raised from about 0.4 m/yr to as much as 3 m/yr. However, it is much more likely that the major ice shelves would continue to be protected, at least in part, by cold, high-salinity water that lies on the continental shelf.

In the case of the West Antarctic Ice Sheet, the situation is further complicated by the possibly delicate stability of the interaction between ice streams and ice shelves. If melting from the base of ice shelves were to increase markedly, the effect on ice streams could be far more important than the expected minor increase in surface melting and runoff. It is difficult to estimate rates because of uncertainties in knowledge of the heat transfer from the ocean to the ice shelves, the effect of ice-shelf thinning on the ice streams, and the mechanism of ice-shelf calving. On the other hand, increased accumulation due to a CO_2-enhanced atmosphere could contribute to sea-level fall.

Estimates of the contribution of glacial wastage to sea level for an atmosphere with a doubled concentration of CO_2 are given in Table 2.

For the time scales longer than one century, the uncertainty in estimating potential changes in land ice and sea level increases significantly. The workshop participants did not attempt to make estimates beyond the year 2100, and the limits expressed in Table 2 should not be extrapolated beyond that year.

The workshop participants accept the importance of these general goals as essential to improvement in our ability to understand and predict sea-level change in the next century:

- Improve existing climate models especially in the treatment of clouds and sea ice, the simulation of high-latitude processes, and the development of time-dependent simulations.
- Determine the present-day global change in sea level more precisely.
- Determine to what extent the current rise in sea level is due to volume expansion of the ocean.

The following specific recommendations concern our ability to understand and predict the response of glaciers and ice sheets to an altered climate in the next century. These recommendations are all considered important to reducing uncertainties and are listed in order of decreasing priority based on amount of uncertainty that might be removed; priorities are assigned across the various disciplines. These recommendations are explained in greater detail in Section 6.3.

Table 2. Estimates of the Contribution to Sea-Level Rise by Ice Wastage in a CO_2-Enhanced Environment[a]

Ice Mass	Annual Probable Contribution to Sea Level with Steady-State $2 \times CO_2$ Atmosphere (mm/yr)	Range of Estimated Contribution to Total Sea-Level Change to Year 2100 (m)	Report Section
Glaciers and small ice caps	2 to 5	0.1 to 0.3	4.2
Greenland Ice Sheet	1 to 4	0.1 to 0.3	4.3
Antarctic Ice Sheet	−3 to 10	−0.1 to 1[b]	5.3

[a]For explanation of assumptions and scenarios involved, see Table 4. Note that thermal expansion of the oceans and other nonglacial processes that might cause additional sea-level rise are not included here.
[b]Values in the range of 0 to 0.3 m are considered most likely.

1. Southern Ocean Circulation near Antarctica (Sections 3.2, 5.2)
   - Assess ocean heat transport across the continental shelf around Antarctica, especially in the Ross, Amundsen, Bellingshausen, and Weddell Sea sectors.
   - Determine ocean circulation beneath the large ice shelves.
   - Analyze how these conditions will change as a result of a CO_2-enhanced atmosphere.
2. Ocean/Ice Shelf Interactions (Sections 5.2 to 5.4)
   - Measure present basal-melt rates and investigate their relationship to underlying ocean circulation.
   - Investigate iceberg calving rates, and identify those factors that affect these rates and determine the seaward boundary of ice shelves.

3. Ice Streams (Section 5.3)
   - Determine the factors controlling whether an ice stream flows in a rapid or slow mode.
   - Compile a complete set of data on ice streams, including such items as their dimensions, slopes, and speeds.
4. Detection and Prediction of Future Changes (Sections 3.1–3.6, 4.1–4.3)
   - Measure changes in dimensions and discharge rates of glaciers and ice sheets.
   - Determine changes in sea level and ocean temperature.

GLOSSARY OF TERMS

This *Glossary* contains definitions of selected CO_2-related terms and units of conversion. Each term is defined in the first few lines, followed by a detailed description, if required. The definitions have been edited for clarity and conciseness, emphasizing the relationship to CO_2 and climate. References to the literature from which the definitions were taken are listed at the end of the *Glossary*.

acidity profile—Determination of the acid concentration in ice core layers as a function of depth using electrical measurements. The magnitudes of some volcanic eruptions in the Northern Hemisphere have been estimated from the acidity of annual layers in ice cores taken in Greenland. This methodology is sometimes referred to as "acidity signal" or "acidity record." [1,2]

advection—The predominately horizontal or isobaric (equal pressure) large-scale motions of the atmosphere. In oceanography, advection is the horizontal or vertical flow of sea water as a current. [3]

aerosol—Particulate material, other than water or ice, in the atmosphere ranging in size from approximately 10^{-3} to larger than 10^2 μm in radius. Aerosols are important in the atmosphere as nuclei for the condensation of water droplets and ice crystals, as participants in various chemical cycles, and as absorbers and scatterers of solar radiation, thereby influencing the radiation budget of the earth-atmosphere system, which in turn influences the climate on the surface of the earth. [4]

albedo—The percentage of electromagnetic radiation incident upon a body that is reflected by it. [5]

alkalinity—A pressure- and temperature-independent property of seawater that is important in determining the carbon composition of seawater. Carbonate alkalinity is the sum of the concentration of bicarbonate plus two times the concentration of the carbonate ions. Total alkalinity is the amount of acid required to bring seawater to a pH at which all dissolved inorganic carbon becomes freely exchangeable. The alkalinity of the oceans is determined, using potentiometric or normal titration techniques, by the presence of bicarbonate, carbonate, and borate ions. [6–8]

atmosphere—The envelope of air surrounding the earth and bound to it by the earth's gravitational attraction. Studies of the chemical properties, dynamic motions, and physical processes of this system constitute the field of meteorology. [9]

biomass—The total dry organic matter or stored energy content of living organisms that is present at a specific time in a defined unit (community, ecosystem, crop, etc.) of the earth's surface. [10,11]

biosphere—The part (reservoir) of the global carbon cycle that includes living organisms (plants and animals) and life-derived organic matter (litter, detritus). The terrestrial biosphere includes the living biota (plants and animals) and the litter and soil organic matter on land, and the marine biosphere includes the biota and detritus in the oceans. [12]

buffer factor (Revelle factor)—The ratio of the instantaneous fractional change in the partial pressure of CO_2 (pCO_2) exerted by seawater to the fractional change in total CO_2 dissolved in the ocean waters. The buffer factor relates the partial pressure of CO_2 in the ocean to the total ocean CO_2 concentration at constant temperature, alkalinity and salinity. The Revelle factor is a useful parameter for examining the distribution of CO_2 between the atmosphere and the ocean, and determines in part the amount of CO_2 that can be dissolved in the mixed surface layer. [13–16]

carbon budget—The balance of the exchanges (incomes and losses) of carbon between the carbon reservoirs or between one specific loop (e.g., atmosphere - biosphere) of the carbon cycle. An examination of the carbon budget of a pool or reservoir can provide information about whether the pool or reservoir is functioning as a source or sink for CO_2. [17,18]

carbon cycle—All parts (reservoirs) and fluxes of carbon; usually thought of as a series of the four main reservoirs of carbon interconnected by pathways of flux. The four reservoirs, regions of the earth in which carbon behaves in a systematic manner, are the atmosphere, terrestrial biosphere (usually includes fresh water systems), oceans, and sediments (includes fossil fuels). Each of these global reservoirs may be subdivided into smaller pools ranging in size from individual communities or ecosystems to the total of all living organisms (biota). Carbon exchanges between the reservoirs by various chemical, physical, geological, and biological processes. [19–21]

carbon density—The amount of carbon per unit area for a given ecosystem or vegetation type, based on climatic conditions, topography, vegetative cover type and amount, soils, and maturity of the vegetative stands. [22]

carbon dioxide fertilization—Enhancement of growth or in the net primary production due to CO_2 enrichment that could occur in natural or agricultural systems as a result of an increase in the atmospheric concentration of CO_2. [21]

carbon flux—The rate of exchange of carbon between the pools (reservoirs) and is usually expressed as Gt C per year. [22]

carbon pool—The reservoir containing carbon as the principal element in the geochemical cycle. [22]

carbon sink—A pool (reservoir) that absorbs or takes up released carbon from another part of the carbon cycle. For example, if the net exchange between the biosphere and the atmosphere is toward the atmosphere, the biosphere is the source and the atmosphere is the sink. [19,20]

carbon source—A pool (reservoir) that releases carbon to another part of the carbon cycle. [19.20]

carbon-based resources—The recoverable fossil fuel reserves (coal, gas, crude oils, oil shale, and tar sands) and biomass that can be used in fuel production and consumption. [23]

climate change—The long-term fluctuations in temperature, precipitation, wind and all other aspects of the earth's climate. External processes such as solar irradiance variations, variations of the earth's orbital parameters (eccentricity, precession, and inclination), lithosphere motions, and volcanic activity are factors in climatic variation. Internal variations of the climate system also produce fluctuations of sufficient magnitude and variability to explain observed climate change through the feedback processes interrelating the components of the climate system. [24]

climate—The statistical collection and representation of the weather conditions for a specified area during a specified time interval, usually decades, together with a description of the state of the external system or boundary conditions. The properties which characterize the climate include thermal (surface air temperatures, water, land, ice), kinetic (wind and ocean currents, together with associated vertical motions and the motions of air masses, aqueous humidity, cloudiness and cloud water content, groundwater, lake lands and water content of snow on land and sea ice), and static (pressure and density of the atmosphere and ocean, composition of the dry air, salinity of the oceans, and the geometric boundaries and physical constants of the system). These properties are interconnected by the various physical processes such as precipitation, evaporation, infrared radiation, convection, advection, and turbulence. [25,26]

climate system—The five physical components (atmosphere, hydrosphere, cryosphere, lithosphere, and biosphere) that are responsible for the climate and its variations. [25]

climate variation—The change in one or more climatic variables over a specified time. [26]

climatic anomaly—The deviation of a particular climatic variable from the mean or normal over a specified time. [25,26]

climatic optimum—The period in history from about 5000–2500 B.C. during which surface air temperatures were warmer than at present in nearly all regions of the world. In the Arctic region, the temperature rose many degrees and in temperate regions, the increase was 1.0°–1.7°C. In this period, there was a great recession of glaciers and ice-sheets, and the melt-water raised sea level by about 3 meters. [27,28]

cloud—A visible mass of condensed water vapor particles or ice in the form of ice, fog, mist or haze suspended above the earth's surface. Clouds may be classified on their visual appearance or form of the cloud or cloud height. [29]

cloud albedo—Reflectivity which varies from less than 10 to over 90% of the insolation and depends on drop sizes, liquid water content, water vapor content, thickness of the cloud and the sun's zenith distance. The smaller the drops and the greater the liquid water content, the greater the cloud albedo, if all other factors are the same. [29]

cloud feedback—The coupling between cloudiness and surface air temperature in which an increase in surface air temperature serves to increase the evaporation; this in turn serves to increase the extent of cloud cover. Increased cloud cover then reduces the solar radiation reaching the earth's surface, thereby lowering the surface temperature. This is an example of negative feedback and does not include the effects of longwave radiation, and the advection in the oceans and the atmosphere, which must also be considered in the overall relationship of the climate system. An increase in middle and low-level clouds could increase the surface albedo, decrease the net downward solar radiation, decrease the surface air temperature, and cool the atmosphere-earth-ocean system, resulting in a negative feedback. On the other hand, an increase in high-level clouds could increase the absorption of solar radiation, decrease the net outgoing radiation, increase surface air temperatures, and heat the atmosphere-earth-ocean system, resulting in positive feedback. [30,31]

convection—Atmospheric motions that are predominately vertical, resulting in vertical transport and mixing of atmospheric properties. Since the most striking meteorological features result if convective motion occurs in conjunction with the rising current of air (i.e., updrafts), convection is sometimes used to imply only upward vertical motion. [32]

convective adjustment—A numerical procedure applied in radiative-convective models to approximate the vertical non-radiative heat transport. This procedure adjusts the lapse rate whenever the latter is exceeded in the numerical iterations of the model and serves to maintain the existing atmospheric temperature distribution. [32]

cryosphere—The portion of the climate system consisting of the world's ice masses and snow deposits, and includes the continental ice sheets, mountain glaciers, sea ice, surface snow cover, and lake and river ice. Changes in snow cover on the land surfaces are by and large seasonal and closely tied to the mechanics of atmospheric circulation. The glaciers and ice sheets are closely related to the global hydrologic cycle and to variations of sea level and change in volume and extent over periods ranging from hundreds to millions of years. [33]

CO_2 reference gas—A mixture of a known quantity of CO_2-in-air or CO_2-in-N_2 used to calibrate carbon dioxide analyzers. [34]

deforestation—The removal of forest stands by cutting and burning to provide land for agricultural purposes, residential or industrial building sites, roads, etc., or by harvesting the trees for building materials or fuel. Oxidation of organic matter releases CO_2 to the atmosphere. Regional and global impacts may result from the release of CO_2 to the atmosphere at a rate similar to that for fossil fuel releases. [35,36]

dendroclimatology—The use of tree growth rings as proxy climate indicators. Tree rings record responses to a wider range of climatic variables over a larger part of the earth than any other type of annually dated proxy record. [37,38]

dendrochronology—The dating of past events and variations in the environment and the climate by studying the annual growth rings of trees. The approximate age of a temperate forest tree can be determined by counting the annual growth rings in the lower part of the trunk. The width of these annual rings is indicative of the climatic conditions during the period of growth; wide annual rings signify favorable growing conditions, absence of diseases and pests, and favorable climatic conditions, while narrow rings indicate unfavorable growing conditions or climate. The most sensitive (variability in ring widths) tree ring chronologies come from trees whose growth has been limited in some way by climatic or environmental factors. [39,40,41]

desertification—The progressive destruction or degradation of vegetative cover especially in arid or semiarid regions bordering existing deserts. Overgrazing of rangelands, large-scale cutting of forests and woodlands, drought and burning of extensive areas all serve to destroy or degrade the land cover. The climatic impacts of this destruction include increased sulfur albedo leading to decreased precipitation which in turn leads to less vegetative cover; increased atmospheric dust loading could lead to decreased monsoon rainfall and greater wind erosion and/or atmospheric pollution. [42]

downwelling—The process of accumulation and sinking of warm surface waters along a coastline. A change of air flow of the atmosphere can result in the sinking or downwelling of warm surface water. The resulting reduced nutrient supply affects the ocean productivity and meteorological conditions of the coastal regions in the downwelling area. [43]

dust veil index—A quantitative methodology developed by H.H. Lamb for calculating the magnitude of volcanic eruptions. The formulae use observations either of the depletion of the solar beam, temperature lowering in middle latitudes, or the quantity of solid matter dispersed as dust. The reference dust veil index is 1000, assigned to the Krakatoa 1883 eruption, and the index is calculated using all three methods where the information is available for statistical comparison purposes. (Abbreviated D.V.I.). [44]

El Niño phenomenon—An irregular variation of ocean current that from January to March flows off the west coast of South America, carrying warm, low salinity, nutrient-poor water to the south. It does not usually extend farther than a few degrees south of the equator, but occasionally it does penetrate beyond 12°S, displacing the relatively cold Peru Current. The effects of this phenomenon are generally short-lived and fishing is only slightly disrupted. Occasionally (in 1891, 1925, 1941, 1957–58, 1965, 1972–73, 1976, and 1982–83), the effects are major and prolonged. Sea surface temperatures rise along the coast of Peru and in the equatorial eastern Pacific Ocean. These sea surface temperatures may remain high for more than a year, having disastrous effects on marine life and fishing. Excessive rainfall and flooding occur in the normally dry coastal area of western tropical South America. Oceanographers and meteorologists refer to the major, prolonged events as El Niño phenomenon rather than the annually occurring weaker and short-lived events of the Southern Oscillation. [45–48]

energy balance models—Models in which the atmospheric physics are neglected completely or very highly parameterized. In the zero-dimensional models, only the incoming and outgoing radiation is considered. The outgoing infrared radiation is a linear function of global mean surface air temperature and the reflected solar radiation is dependent on the surface albedo. The albedo is a step function of the global mean surface air temperatures, and equilibrium temperatures are computed for a range of values of the solar constant. The one-dimensional models have surface air temperature as a function of latitude. At each latitude, a balance between incoming and outgoing radiation and horizontal transport of heat is computed. (Abbreviated as EBM). [49]

feedback mechanisms–A sequence of interactions in which the final interaction influences the original one. See also positive feedback mechanisms and negative feedback mechanisms. [50]

first detection—Identification of a "precursor signal," detectable above the "noise" of natural climatic variability, of a significant change in a climate parameter, and attribution of this change to an increase in atmospheric carbon dioxide concentrations. The signal may be estimated by numerical modeling of the climate, and the noise can be estimated using instrumental data. For any modeled signal that is estimated, the corresponding noise can be estimated from observational data, and a signal-to-noise ratio can be calculated to provide a quantitative measure of detectability. [51–53]

general circulation models—Hydrodynamic models of the atmosphere on a grid or spectral resolution which determine the surface pressure and the vertical distributions of velocity, temperature, density and water vapor as a function of time from the mass conservation and hydrostatic laws, the first law of thermodynamics, Newton's second law of motion, the equation of state and the conservation law for water vapor. (Abbreviated as GCM). Atmospheric general circulation models are abbreviated AGCM while oceanic general circulation models are abbreviated OGCM. [54]

greenhouse effect—Gases, such as carbon dioxide, ammonia and water vapor, which are transparent to incoming shortwave radiation, but are relatively opaque to outgoing longwave radiation, are said to be "radiatively active." Variations in their concentration can alter the thermal balance of the earth's atmosphere and disturb its energy balance. Outgoing terrestrial radiation, which would otherwise escape to space, is thus trapped within the lower levels of the atmosphere, resulting in a "greenhouse effect" due to the rise in surface temperatures and cooling of upper levels of the atmosphere. Other minor trace gases, including the manmade chlorofluorocarbons, may also have caused a greenhouse warming in the 1970's comparable to that attributed to increasing atmospheric carbon dioxide concentrations. [55]

gross primary productions—The total amount or weight of organic matter created by photosynthesis over a defined time period (total product of photosynthesis). [56]

gyres—Major circulating flow patterns in the oceans. The wind-driven eastward and westward flowing equatorial currents are blocked by the continents and rotate slowly in a clockwise direction in the North Atlantic and Pacific Oceans, and in a counterclockwise direction in the South Atlantic, South Pacific and Indian Oceans. [57,58]

Hadley cell—A direct thermally-driven and zonally symmetric large-scale atmospheric circulation first proposed by George Hadley in 1735 as an explanation for the trade winds. It carries momentum, sensible heat and potential heat from the tropics to the mid-latitudes (30°). The northernward transport aloft is complemented by subsidence in the subtropical high pressure ridge and a surface return flow. The variability of this cell and the Walker cell is hypothesized to be a major factor in short-term climatic change. [65,75]

Holocene—The most recent epoch of the Quaternary period covering approximately the last 100,000 years. [28]

hydrologic cycle—The process of evaporation, vertical and horizontal transport of vapor, condensation, precipitation, and re-evaporation of water between the earth, the atmosphere, and the oceans. It is a major factor in determining climate through its influence on surface vegetation, the clouds, snow and ice, and soil moisture. The hydrologic cycle is responsible for 25 to 30 percent of the mid-latitudes' heat transport from the equatorial to polar regions. [59]

hydrosphere—The portion of the earth's surface covered by water, in either the solid or liquid state. Approximately 74 percent of the earth's surface is covered by water in the form of oceans, freshwater lakes, rivers, saline lakes and inland seas, icecaps and glaciers, soil moisture and vadose water, and groundwaters. Circulation of the waters in the hydrosphere results in the weathering of the landmasses and evaporation of water from the earth's surface results in precipitation. [60]

Hypsithermal period—The period about 5000 to 8000 years ago when the earth was apparently several degrees warmer than it is now. More rainfall occurred in most of the subtropical desert regions and less in the central midwest United States and Scandinavia. It is also called the "altithermal period" and can serve as a past climate analog for predicting climate change due to an increase in atmospheric carbon dioxide concentrations, [27,28]

ice/snow-albedo-temperature feedback—Interactions that can be described as a theoretical concept of a feedback mechanism in which the interacting elements are the areal extent of polar ice and snow cover, the albedo of the polar region (dependent on areal extent of ice and snow), absorption of solar radiation (dependent on the albedo), temperature (dependent on the absorption of solar radiation) and the area of ice and snow cover (dependent on temperature). Less snowfall would mean more absorption of solar radiation, therefore a surface warming would occur. Climate modeling studies indicate an amplification effect, i.e., positive feedback of the ice/snow-albedo feedback on increased surface air temperatures caused by increases in the atmospheric concentration of carbon dioxide. [50]

ice and snow albedo—The reflectivity of ice and snow-covered surfaces. The albedo of freshly fallen snow may be as much as 90%, while older snow may have values of 75% or less. The larger the areal extent of snow and ice cover, the higher the albedo value. The surface albedo will also increase as a function of the depth of snow cover (maximum 12.7 cm) and be unaffected by increased snow cover after reaching that depth. [5,61]

infrared radiation—Electromagnetic radiation lying in the wavelength interval from 0.7 μm to 1000 μm (0.1 cm). Its' lower limit is bounded by visible radiation, and its' upper limit by microwave radiation. Infrared radiation is generated almost entirely by large-scale intra-molecular processes. The triatomic gases, such as water vapor, carbon dioxide, and ozone, are infrared-active and play important roles in the propagation of infrared radiation in the atmosphere. (Abbreviated IR; also called "longwave radiation"). [3,62]

insolation—The radiant energy reaching a unit horizontal area of the earth in the form of electromagnetic radiation from the sun reaching the top of the atmosphere. It is sometimes referred to as "solar irradiance." The latitudinal variation of insolation supplies the energy for the general circulation of the atmosphere. Insolation outside the earth's atmosphere depends on the angle of incidence of the solar beam and on the solar constant. [62]

lapse rate—The vertical temperature gradient and is based on the supposition that air is not moving vertically. When the air does move upward or downward, the motion causes the temperature to change at a rate which is a function of the changing pressure upon it. The normal lapse rate is defined to be 3.6°F per 1000 feet change in altitude. The dry adiabatic lapse rate is about 5.5°F per 1000 feet and the wet adiabatic lapse rate varies between 2 and 5°F per 1000 feet. [64,65]

latent heat—Energy transfered from the earth's surface to the atmosphere through the evaporation and condensation processes.

lithosphere—The component of the earth's surface comprising the rock, soil and sediments. It is a relatively passive component of the climate system and its physical characteristics are treated as fixed elements in the determination of climate. The soil moisture component is an exception and is closely related to the local surface and ground hydrology. [60]

Little Ice Age—A cold period that lasted from A.D. 1550-1600 to about A.D. 1850 in Europe, North America, and Asia. This period had rapid expansion of mountain glaciers, especially in the Alps, Norway, Ireland, and Alaska. There are three maxima, beginning about 1650, about 1770, and 1850, each separated by slight warming intervals. [27,28]

longwave radiation—The radiation emitted in the spectral wavelength greater than 4 μm corresponding to the radiation emitted from the earth and atmosphere. It is sometimes referred to as terrestrial radiation or "infrared radiation." [62]

Mauna Loa record—The record of measurements of atmospheric carbon dioxide concentrations taken at the Mauna Loa Observatory, Mauna Loa, Hawaii, beginning in March 1958 and continuing to the present. The Mauna Loa record is the longest reliable daily record of atmospheric carbon dioxide measurements in the world. [66]

mean sea level—The average height of the sea surface, based upon hourly observation of the tide height on the open coast or in adjacent waters that have free access to the sea. In the United States, it is defined as the average height of the sea surface for all stages of the tide over a nineteen year period. Mean sea level, commonly abbreviated as MSL and referred to simply as "sea level," serves as the reference surface for all altitudes in upper atmospheric studies. [67]

Milankovitch effect—The mathematical theory of astronomically determined climates which requires that for a glacial age to occur, northern high latitude summer must be cold to prevent the winter snow from melting in such a way as to allow a positive value in the annual budget of snow and ice, and to initiate a positive feedback cooling over the earth through a further extent of the snow cover and subsequent increased surface albedo. [55,69]

monsoon—A name for seasonal winds, first applied to the winds over the Arabian Sea which blow for six months from the northeast and for six months from the southwest. The term has been extended to similar winds in other parts of the world, *i.e.*, the prevailing west to northwest winds of summer in Europe have been called the "European monsoon." The primary cause for these seasonal winds is the much greater annual variation of temperature over large land areas compared with neighboring ocean surfaces, causing an excess of pressure over the continents in winter and a deficit in summer, but other factors such as topography of the land also have an effect. The monsoons are strongest in the southern and eastern sides of Asia, but also occur in the coasts of tropical regions wherever the planetary circulation is not strong enough to inhibit them. The monsoon climate can be described as a long winter-spring "dry season" which includes a "cold season" followed by a short "hot season" just preceding the rains; a summer and early autumn rainy season which is generally very wet but may vary greatly from year to year; and a secondary maximum of temperature immediately after the rainy season. [3]

negative feedback—An interaction that causes a reduction or dampening of the response of the system in which it is incorporated. [50]

net primary production—The part of the gross primary production that remains stored in the producer organism (primarily green plants) after deducting the amount used during the process of respiration. [56]

ocean mixing processes—The rates of advection, upwelling/downwelling, and eddy diffusion that are important in determining how rapidly excess atmospheric carbon dioxide can be taken up by the oceans. [69,70]

palynology—The science of reconstruction of the past flora and vegetation and past climate using pollen data obtained from lake and bog sediments. The fossil pollen record is a function of the regional flora and vegetation at a given time and location.

past climate analogs—The reconstruction of past climates at a given locality using modern climatic conditions in a different elevation or latitudinal zone to infer past climatic conditions. [68]

pCO_2—The partial pressure of CO_2 in the atmosphere and the ocean. In the atmosphere, the partial pressure of CO_2 is defined as the pressure the CO_2 would exert if all other gases were removed. The sum of the partial pressure of all the atmospheric gases will equal the atmospheric pressure. The partial pressure of CO_2 in the atmosphere is determined by the atmospheric CO_2 in the atmosphere is determined by the atmospheric CO_2 concentration and atmospheric temperature. In the ocean the pCO_2 is determined by the amount of dissolved CO_2 and H_2CO_3. It varies with total CO_2, alkalinity, latitude, depth, and temperature. Biological processes in the ocean also exert an influence on the pCO_2 in the ocean. [70,71]

photosynthesis—The process by which green plants use light to synthesize organic compounds (primarily carbohydrates) from carbon dioxide and water, using light absorbed by chlorophyll as an energy source. Oxygen and water vapor are released in the process. Photosynthesis is dependent on favorable temperature and moisture conditions as well as on the atmospheric carbon dioxide concentration. Increased levels of carbon dioxide can increase net photosynthesis in many plants. [72,73]

planetary boundary layer—The transition region between the turbulent surface layer and the normally nonturbulent free atmosphere. This region is about 1 km in thickness and is characterized by a well-developed mixing generated by frictional drag as the air masses move on the earth's surface. This layer contains approximately 10% of the mass of the atmosphere. (Also called "atmospheric boundary layer" or "frictional layer."). [74]

positive feedback—An interaction that causes an amplification of the response of the system in which it is incorporated. [50]

precipitation—Any or all forms of liquid or solid water particles that fall from the atmosphere and reach the earth's surface. It includes drizzle, rain, snow, snow pellets, snow grains, ice crystals, ice pellets, and hail. The ratio of precipitation to evaporation is the most important factor in the distribution of vegetation zones. Precipitation is also defined as a measure of the quantity, expressed in centimeters or milliliters of liquid water depth, of the water substance that has fallen at a given location in a specified amount of time. [75,76]

primary productivity—The rate at which radiant energy is photosynthetically and chemosynthetically stored by producer organisms (primarily green plants) as organic compounds, per unit area, per unit time. [56,77]

proxy climate indicators—Dateable evidence of a biological or geological phenomenon whose condition, at least in part, is attributable to climatic conditions at the time of its formation. Proxy data are any material that provides an indirect measure of climate and include documentary evidence of crop yields, harvest dates, glacier movements, tree rings, varves, glaciers and snow lines, insect remains, pollen remains, marine microfauna, isotope measurements: ^{18}O, in ice sheets, ^{18}O, ^{2}H, and ^{13}C in tree rings; $CaCO_3$ in sediments; and speleotherms. There are three main problems in using proxy data: (1) dating, (2) lag and response time and (3) meteorological interpretation. Tree rings, pollen deposits from varved lakes, and ice cores are the most promising proxy data sources for reconstructing the climate of the last five millennia, since the dating are precise on an annual basis, while other proxy data sources may only yield data on a 50 ± 100 years timescale. [78]

Quaternary period—The last two million years of the earth's history. It is divided into two epochs: **Pleistocene**—2 million years ago to approximately 100,000 years ago and the **Holocene**—the period from approximately 100,000 years ago to the present. The Quaternary period is the artificial division of time separating prehuman and human periods. It contains five ice ages and four interglacial ages and temperature indicators seem to show sharp and abrupt changes by several degrees. [28]

radiation balance—The difference between the absorbed solar radiation and the net infrared radiation. Experimental data show that radiation from the earth's natural surfaces is rather close to the radiation from a black body at the corresponding temperature; the ratio of the observed values of radiation to black body radiation is generally 0.90–1.0. [62]

radiative-convective models—Thermodynamic models that determine the equilibrium temperature distribution for an atmospheric column and the underlying surface, subject to prescribed solar radiation at the top of the atmosphere and prescribed atmospheric composition and surface albedo. Submodels for the transfer of solar and terrestrial radiation, the heat exchange between the earth's surface and atmosphere, the vertical redistribution of heat within the atmosphere, the atmospheric water vapor content and clouds are included in these one-dimensional models. (Abbreviated as RCM). [54]

radiosonde—A balloon-borne instrument for the simultaneous measurement and transmission of meteorological data up to a height of approximately 30,000 meters (100,000 feet). The height of each pressure level of the observation is computed from data received via radio signals. [3]

residence time—The size of any specific reservoir or pool of mass (e.g., carbon) divided by the total flux of mass into or out of that pool. [79]

respiration—A biochemical process by which living organisms take up oxygen from the environment and, in the case of plants, consume some of the photosynthate (organic matter produced by photosynthesis) they have synthesized during daylight hours, or in the case of animals, both carbon dioxide and heat are released during respiration. [80]

rocketsonde—A rocket-borne instrument for measurement and transmission of upper-air meteorological data in the lower 76,000 meters (250,000 feet) of the atmosphere, especially that portion inaccessible to radiosonde techniques. [3]

seasonal variation—The change in a set of meteorological parameters averaged over a season. Seasonal variation is the largest climatic variation and temperature is the most frequently observed meteorological parameter. Often, monthly averaged data are grouped into seasons, according to the prescribed definition. [26]

sea surface temperature—The temperature of the layer of seawater (approximately 0.5 m depth) nearest the atmosphere, generally determined either by bucket or injection methods. The bucket measurement is obtained by lowering a water-temperature thermometer provided with an insulated container around the bulb, allowing the thermometer to reach the temperature of the surface water, then withdrawn and the temperature recorded. The injection method measures the temperature of the water at the water-intakes in an engine room of a vessel and is the standard used today. [81]

secular carbon dioxide trend—The fairly uniform and accelerating increase of carbon dioxide concentration in the atmosphere, as illustrated by the Mauna Loa record. The secular trend reflects the increase in global atmospheric carbon dioxide concentrations due to combustion of fossil fuels, kilning of limestone, and possibly a net biospheric release of carbon dioxide resulting from deforestation. [82]

sensible heat—The mechanism of transferring excess radiative energy from the earth's surface to the atmosphere through advection, the conduction and convection processes. [63]

shortwave radiation—The radiation received from the sun and emitted in the spectral wavelengths less than 4 μm. It is also called "solar radiation." [62]

signal-to-noise ratio—A quantitative measure of detectability of a signal to the observed noise of a parameter. For first detection of a CO_2-induced climate change, the model signal is the mean change or anomaly in some climatic variable, usually surface air temperature, attributed by a numerical model to increased concentrations of carbon dioxide. Observed noise is the standard deviation or natural variability computed from observations of that variable and adjusted for sample size, autocorrelation, and time averaging. [51–53]

soil carbon—A major component of the terrestrial biosphere pool in the carbon cycle. Organic soil carbon estimates, rather than total soil carbon, are generally quoted. The amount of carbon in the soil is a function of historical vegetative cover and productivity, which in turn is dependent upon climatic variables. [83,84]

Southern Oscillation—A large-scale atmospheric and hydrospheric fluctuation centered in the equatorial Pacific Ocean, which consists of wind strengths, ocean currents, and sea-surface temperatures. It has a variable period, averaging about 4 years. El Niño occurrences are associated with the Southern Oscillation. Southern Oscillation indexes can be formulated based on the pressure gradient between the quasi-stationary low pressure region. A positive index corresponds to an anomalously high pressure difference between the centers of action. [85–88]

statistical-dynamical models—Models which treat the dynamical processes statistically by relating them parametrically to temperature and temperature gradients. The major difference between these models and the general circulation models (GCMs) is the degree and scale of the parameterized processes. (Abbreviated as SDM). [54]

stratosphere—The region of the upper atmosphere extending upward from the tropopause (8 to 15 km altitude). The thermal structure is determined by its radiation balance and is generally very stable with low humidity. [9]

Suess effect—The relative change in the $^{14}C/C$ or $^{13}C/C$ ratio of any carbon pool or reservoir caused by the addition of fossil fuel CO_2 to the atmosphere. Fossil fuels are devoid of ^{14}C, due to the radioactive decay of ^{14}C to ^{14}N during long underground storage, and are depleted in ^{13}C, due to isotopic fractionation eons ago during photosynthesis by the plants that were the precursors of the fossil fuels. Carbon dioxide produced by the combustion of fossil fuels is thus virtually free of ^{14}C and depleted in ^{13}C. The term "Suess effect" originally referred to the dilution of the $^{14}C/C$ ratio in atmospheric CO_2 due to the admixture of fossil fuel produced CO_2, but the definition has been extended to both the ^{14}C and ^{13}C ratios in any pool or reservoir of the carbon cycle resulting from human disturbances. [89]

sunspot—A relatively dark, sharply defined region on the solar disk, marked by an umbra approximately 2000K cooler than the effective photospheric temperature, surrounded by a less dark but also sharply bounded penumbra. The average spot diameter is about 3700 km, but can range up to 245,000 km. Most sunspots are found in groups of two or more, but they can occur singly. Sunspots are cyclic, with a period of approximately 11 years. The quantitative definition of sunspot activity is called the Wolf sunspot number, denoted R. The Wolf sunspot number is also referred to as "Wolfer sunspot number," "Zurich relative sunspot number" or "relative sunspot number." [90,91]

surface air temperature—The temperature of the air near the surface of the earth, almost invariably determined by a thermometer in an instrument shelter about 2 meters above the ground. Daily means, obtained as an average of minimum and maximum readings, are reduced to monthly or annual averages. The true daily mean, obtained from a thermograph, is approximated by the mean of 24 hourly readings and may differ by 0.5–1.0°C from the average based on minimum and maximum readings. The global average surface air temperature is 15°C. [3,5]

surface albedo—The ratio of solar irradiation reflected from the ground to the impinging irradiation on the surface. Reflectivity varies with ground cover and during the winter months it varies greatly with the amount of snow cover (depth and areal extent). Roughness of terrain, moisture content, solar angle, angular and spectral distribution of ground level irradiations are other factors affecting surface albedo. [3,5]

terrestrial radiation—The total infrared radiation emitted from the earth's surface. The atmosphere emits, absorbs, and transmits radiation, and the net flux of radiation at any one point depends upon the distribution with height of temperature and water vapor. Terrestrial radiation provides a major part of the potential energy charges necessary to drive the atmospheric wind system and is responsible for maintaining the surface air temperature within limits for livability. [92]

thermocline—A transition layer of water in the ocean, with a steeper vertical temperature gradient than that found in the layers of ocean above and below. The permanent thermocline separates the warm mixed surface layer of the ocean from the cold deep ocean water, and is found between 100—1000 meter depths. The thermocline first appears at the 55—60° N and S latitudes, where it forms a horizontal separation between temperature and polar waters. The thermocline reaches its maximum depth at mid-latitudes and is shallowest at the equator and at its northern and southern limits. The thermocline is stably stratified, and transfer of water and carbon dioxide across this zone occurs very slowly. Thus, the thermocline acts as a barrier to the downward mixing of carbon dioxide. [93,94]

trace gas—A minor constituent of the atmosphere with strong infrared absorption bands within the 7 to 14 μm (700 to 1400 cm^{-1}) atmospheric window that transmits most of the thermal radiation from the earth's surface and lower atmosphere. The more important trace gases of interest in carbon dioxide research are water, carbon dioxide, ozone, methane, ammonia, nitric acid, nitrous oxide, ethylene, sulfur dioxide, nitric oxide, dichlorofluoromethane or Freon 12, trichlorofluoromethane or Freon 11, methyl chloride, carbon monoxide, and carbon tetrachloride. [95,96]

transient tracers—Chemical elements (often radioactive) or compounds in the ocean that have finite life times. Atmospheric testing of nuclear weapons from the mid-1950's to the early 1960's released large quantities of radionuclides to the atmosphere. Atmosphere-ocean exchange processes have transferred some of these elements to the oceans. Studying the behavior and distribution of these specific isotopes and other chemical tracers in the ocean will provide information on: (a) residence times of the water and its dissolved components in gyres, basins, etc.; (b) the mode and rate of formation and the subsequent spreading rates of specific water types such as the polar water of the Norwegian and Greenland Seas; (c) deep ocean circulation and ocean mixing processes such as advection and upwelling; and (d) the flux of anthropogenic carbon dioxide into the ocean through its correlation with several different transient tracers. [98,99]

transpiration—The process in plants by which water is taken up by the roots and is released as water vapor by the leaves. [80]

tree rings—Annual growth increment of trees that indicate, among other factors, the climatic conditions that enhance or limit growth. Tree ring widths and indices have been used in the search for solar-terrestrial relationships and climatic cycles and climatic reconstructions of past climates. See also "dendroclimatology" and "dendrochronology." [39,40]

troposphere—The inner layer of the atmosphere, between the earth's surface and to about 15 km, within which there is a steady decrease of temperature with increasing altitude. Nearly all clouds form and weather conditions manifest themselves within this region and its thermal structure is due primarily to the heating of the earth's surface by solar radiation, followed by heat transfer by turbulent mixing and convection. [9]

tropopause—The boundary between the troposphere and the stratosphere (about 8 km in polar regions and about 15 km in tropical regions). This boundary is generally defined in terms of points in the vertical air-mass surroundings where the temperature lapse rate becomes less than 2°C/km and marks the vertical limit of clouds and storms. [9]

turnover rate—The fraction of the total amount of mass (e.g., carbon) in a given pool or reservoir that is released from or that enters the pool in a given length of time. Turnover rate of carbon is expressed as Gt C/year. [10]

upwelling—The process of vertical motion of water in the ocean by which sub-surface water of lower temperature and greater density moves toward the surface of the ocean. Upwelling occurs most commonly among the western coastlines of continents, but may occur anywhere in the ocean. Upwelling results when winds blowing nearly parallel to a continental coastline transport the light surface water away from the coast. Sub-surface water of greater density and lower temperature replaces the surface water, and exerts a considerable influence on the weather of coastal regions. Carbon dioxide is transferred to the atmosphere in regions of upwelling. The upwelling of deep water brings water enriched in CO_2 to the surface of the ocean. This is especially important in the Pacific equatorial regions, where one to two Gt of carbon may be released to the atmosphere each year. Upwelling also results in increased ocean productivity by transporting nutrient-rich waters to the surface layer of the ocean. [97]

Walker cell—A zonal circulation confined to equatorial regions and driven principally by the oceanic temperature gradient. In the Pacific, air flows westward from the colder, eastern area to the warm, western ocean where it acquires warmth and moisture, and subsequently rises. A return flow aloft and subsidence over the eastern ocean complete the cell. [65,74]

water stress effect—The closing of the stomata by a plant in response to excessive water loss through transpiration or in response to drought conditions. The stomatal closing reduces CO_2 uptake as well as water loss, thus decreasing the photosynthetic rate. However, under conditions of elevated CO_2 concentration, the CO_2 gradient between the atmosphere and the leaf is higher than under ambient conditions, and CO_2 can pass through partially closed stomates in a rate similar to that of low CO_2 and open stomates. The humidity gradient remains the same at high CO_2, and transpiration is impeded. The net result is improved water use efficiency by some plants.

water use efficiency—The "photosynthetic production per unit of water consumed by the plant through transpiration" or the ratio of CO_2 uptake to water vapor loss. [21,72]

water vapor—Water substance in vapor form and the source of all forms of condensation and precipitation. Water vapor and carbon dioxide are the main atmospheric components in the exchange of terrestrial radiation in the troposphere, serving as a regulator of planetary temperatures via the greenhouse effect. Approximately 50 percent of the atmosphere's moisture lies within about 1.84 km of the earth's surface and only a minute fraction of the total occurs above the tropopause. [74]

water vapor feedback—A positive feedback (interaction) process in which an increase in the amount of water vapor increases the absorption of longwave radiation, thereby contributing to a warming of the atmosphere. Warming, in turn, may result in increased evaporation and an increase in the initial water vapor anomaly. This feedback, along with carbon dioxide, is responsible for the greenhouse effect and operates virtually continuously in the atmosphere. [74]

weather—The instantaneous state of the global atmosphere-ocean cryosphere system. [3,25]

zonally-averaged models—Statistical-dynamical models in which only the longitudinally averaged quantities are determined and the effects of the longitudinally varying transports are determined parametrically. (Abbreviated as ZAM). [54]

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TABLES

Table 1. International System of Units (SI): Prefixes

Prefix	SI Symbol	Multiplication Factor
exa	E	10^{18}
peta	P	10^{15}
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
hecto	h	10^{2}
deca	da	10
deci	d	10^{-1}
centi	c	10^{-2}
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}
femto	f	10^{-15}
atto	a	10^{-18}

Table 2. Useful Quantities in CO_2 Research

Quantity	Symbol	Value
Solar constant	f	1.369 kW/m^2
Earth mass	m	5.976×10^{24}kg
Equatorial radius	a	6.378×10^{6}m
Polar radius	c	6.357×10^{6}m
Mean radius	R	6.371×10^{6}m
Surface area	A_e	5.101×10^{14}m^2
Land area	A_l	1.481×10^{14}m^2
Ocean area	A_s	3.620×10^{14}m^2
Ice sheets and glaciers	I_s	0.16×10^{14}m^2
Continental shelf	C_s	0.29×10^{14}m^2
Mean land elevation	h_l	840 m
Mean ocean depth	h_s	3730 m
Mean ocean volume	V_s	1.350×10^{18}m^3
Ocean mass	M_s	1.384×10^{21}kg
Mass of atmosphere	M_a	5.137×10^{18}kg
Equatorial surface gravity	g	9.780 m/s^2

Table 3. Common Conversion Factors

Area-length-volume
- 1 acre = 43,560 ft^2 = 4,047 m^2
- 1 acre-foot = 1.2335×10^3 m^3
- 1 cubic foot (ft^3) = 0.02832 m^3
- 1 hectare (ha) = 10,000 m^2 = 2.47 acres
- 1 square mile (mi) = 2.59×10^6 m^2

Pressure
- 1 atmosphere = 76.0 cm Hg = 1,013 millibars (mb)
- 1 bar = 0.9869 atmosphere
- 1 pascal (Pa) = 1.013×10^5 atmosphere = 100 millibars = 6.895×10^3 pounds per square inch (psi)

Factors for carbon and carbon dioxide
- 1 mole C/liter = 12.011×10^{-3} Gt C/km^3
- 1 ppm by volume of atmosphere CO_2 = 2.130 Gt C
- 12.011 g C = 1 mole CO_2
- 1 g C = 3.667 g CO_2

Source: American Society for Testing and Materials, 1973, *Standard Metric Practice Guide* (Philadelphia: ASTM).

Table 4. Common Energy Unit Conversion Factors

	J	Quad	kcal	mtce	boe	mtoe	m^3 gas	TWyr
1 J =	1	947.9×10^{-21}	239×10^{-6}	34.14×10^{-12}	163.4×10^{-12}	22.34×10^{-12}	26.84×10^{-9}	31.71×10^{-21}
1 Quad =	1055×10^{15}	1	252×10^{12}	36.02×10^{6}	172.4×10^{6}	23.57×10^{6}	28.32×10^{9}	33.45×10^{-3}
1 kcal =	4184	3966×10^{-18}	1	142.9×10^{-9}	683.8×10^{-9}	93.47×10^{-9}	112.3×10^{-6}	132.7×10^{-18}
1 mtce =	29.29×10^{9}	27.76×10^{-9}	7×10^{6}	1	4.786	0.6543	786.1	928.7×10^{-12}
1 boe =	6119×10^{6}	5.8×10^{-9}	1462×10^{3}	0.2089	1	0.1367	164.2	194×10^{-12}
1 mtoe =	44.76×10^{9}	42.43×10^{-9}	10.7×10^{6}	1.528	7.315	1	1201	1419×10^{-12}
1 m^3 gas =	37.26×10^{6}	35.31×10^{-12}	8905	1272×10^{-6}	6089×10^{-6}	832.3×10^{-6}	1	1181×10^{-15}
1 TWyr =	31.54×10^{18}	29.89	7537×10^{12}	1076×10^{6}	5154×10^{6}	704.5×10^{6}	846.4×10^{9}	1

Notes: J = Joule, Quad = Quadrillion Btu (British thermal unit), kcal = kilogram calorie, mtce = metric ton of coal equivalent, boe = barrel of oil equivalent, mtoe = metric ton of oil equivalent, m^3 gas = cubic meter of natural gas, TWyr = Terrawatt-year

Source: Häfele, W., ***Energy in a Finite World: A Global Systems Analysis,*** report by the Energy Systems Program Group of the International Institute for Applied Systems Analysis (Ballinger Publishing Co., Cambridge, Massachusetts), p. 211 (1981).

Table 5. Factors and Units for Calculating Annual CO_2 Emissions Using Global Fuel Production Data

$[CO_{2_i} = (P_i)(FO_i)(C_i)]$*

From Coal Production

CO_{2_s} = CO_2 emissions in 10^6 tons C
P_s = Annual production in 10^6 tons coal equivalent (± ≈ 11.2%)
FO_s = Effective fraction oxidized in year of production = 0.982 ± 2%
C_s = Carbon content in tons C per ton coal equivalent = 0.746** ± 2%

From Natural Gas Flaring

CO_{2_f} = CO_2 emissions in 10^6 tons C
P_f = Annual gas flaring in 10^9 cubic meters (± ≈ 20%)
FO_f = Effective fraction oxidized in year of flaring = 1.00 ± 1%
C_f = Carbon content in tons per thousand cubic meters = 0.525 ± 3%

From Natural Gas Production

CO_{2_g} = CO_2 emissions in 10^6 tons C
P_g = Annual production in thousands of 10^{12} joules (± ≈ 10%)
FO_g = Effective fraction oxidized in year of production = 0.98 ± 1%
C_g = Carbon content in 10^6 tons per thousand 10^{12} joules = 0.0137 ± 2%

From Crude Oil and Natural Gas Liquids Production

CO_{2_l} = CO_2 emissions in 10^6 tons C
P_l = Annual production in 10^6 tons (± ≈ 8%)
FO_l = Effective fraction oxidized in year of production = 0.918 ± 3%
C_l = Carbon content in tons C per ton crude oil = 0.85 ± 1%

*All masses are in metric tons (10^3 kg).

**The 0.746 value includes a heating value adjustment to recognize that the carbon content, developed on a higher heating value basis, must be increased when used with UN production data (UN, 1982) based on "net" or lower heating values.

Source: Marland, G. and R. M. Rotty, *Carbon Dioxide Emissions from Fossil Fuels: A Procedure for Estimation and Results for 1950–1981,* DOE/NBB-0036, TR003, U.S. Department of Energy, Carbon Dioxide Research Division (1983).

GLOSSARY OF ACRONYMS

2B	Two-box model
AAAS	American Association for the Advancement of Science
ACRIM	Active-cavity radiometer
AD	Advection-diffusion model
AER	Atmospheric and Enviromental Research, Inc.
AF	Airborne fraction
AF*	Effective airborne fraction
AGCM	Atmospheric general circulation model
AGU	American Geophysical Union
AHG	Abteilung fur Hydrologie und Glaziologie, VAW
AIT	Action initiation time
AMB	Ambient
AMS	Amsterdam Island
API	American Petroleum Institute
AR0	Autoregressive model of the zeroth order
AR1	First-order autoregressive
ARMA	Autoregressive moving average
ASC	Ascension Island
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing Materials
AVHRR	Advanced (very) high-resolution radiometer
AVI	American Virgin Islands
AZR	Terceira Island, Azores
B-A	Box-advection model
B-A-D	Box-advection-diffusion model
BADJ	Baroclinic adjustment
BAE	Bulk aerodynamic exchange
BAS	British Antarctic Survey
B-B	Two-box model
BD	Box diffusion
B-D	Box-diffusion model
BJMO	Bjorkstrom ocean model
BM	Basal melting
BP	Before the present era
BRW	Barrow, Alaska
BT	Bathythermograph
c	Continental
CAC	Climate Analysis Center
CAENEX	Complex Atmospheric Energetics Experiment
CAM	Crassulacean acid metabolism

CAST	Council for Agricultural Science and Technology
CBA	Cold Bay, Alaska
CBO	Congressional Budget Office, U.S. Congress
CCM	Community climate model
CDIC	Carbon Dioxide Information Center
CDW	Circumpolar deep water
CEC	Commission of the European Communities
CEP	Capable of extrapolative prediction
CER	Carbon exchange rate
CERL	U.K. Central Electricity Research Laboratories
CFC	Chlorofluorocarbons
CFI	Continuous forest inventory
CIO	Conventional international origin
CIP	Capable of interpolative prediction
CIRES	Cooperative Institute for Research in Environmental Sciences
ClC	Chlorocarbons
CLIMAP	Climate: Long-Range Investigation, Mapping, and Prediction
CLR	Clear, no clouds
CMA	Chemical Manufacturers Association
CMO	Cape Meares, Oregon
COADS	Comprehensive ocean-atmosphere data set
COE	Corps of Engineers, U.S. Army
COHMAP	Cooperative Holocene Mapping Project
COS	Cosmos, Peru
CS	Crop species
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CTD	Conductivity-temperature-depth
DG	Davidson Glacier
DISW	Deep ice shelf water
DJF	December-January-February
DOC	Dissolved organic carbon
DOE	U.S. Department of Energy
DS	Drought stressed
DVI	Dust veil index
EA	East Antarctica
EBM	Energy balance model
EGCM	Eddy-resolving ocean general circulation model
EGIG	International Glaciological Expedition to Greenland
EIA	U.S. Energy Information Administration
ELA	Equilibrium-line altitude
ENSO	El Nino/Southern Oscillation
EOF	Empirical orthogonal function
EOR	Enhanced oil recovery
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
ER	Edmonds and Reilly
ER	Ecosystem respiration
ERE	Equivalent radiative exchange
ERGB	Edmonds, Reilly, Gardner, and Brenkert
ERS	European Remote Sensing Satellite
ESA	European Space Agency
ESMR	Electrically scanning microwave radiometer
ETH	Eidgenosche Technische Hochschule, Zurich
FACE	Free air carbon dioxide enrichment

FAGS	Federation of Astronomical and Geophysical Services
FAH	Fixed absolute humidity
FAL	Fixed (surface) albedo
FAO	U.N. Food and Agriculture Organization
FCA	Fixed cloud altitude
FCC	Fixed cloud cover
FCP	Fixed cloud pressure
FCT	Fixed cloud temperature
FGGE	First Global Geophysical Experiment
FLK	Falkland Islands
FLR	Fixed lapse rate
FOD	Fixed optical depth
FOX	Fisheries Oceanography Experiment
FRH	Fixed relative humidity
FY	Fiscal year
GAARS	Global Atmospheric Aerosol and Radiation Study
GAO	General Accounting Office, U.S. Congress
GCM	General circulation model
GDD	Growing degree days
GEOS	Geodetic Earth Observatory Satellite
GEOSAT	Geodesy Satellite
GEOSECS	Geochemical Ocean Sections
GFDL	Geophysical Fluid Dynamics Laboratory
GISS	Goddard Institute for Space Studies
GLA	Goddard Laboratory for Atmospheres
GLM	General linear models
GM	Glacial meltwater
GMCC	Geophysical Monitoring for Climatic Change
GMI	Guam, Marshall Islands
GNP	Gross national product
GPP	Gross primary production
GPS	Global Positioning Satellite
Gt C	Gigatons of carbon
HBA	Halley Bay, Alaska
HI	Harvest index
HIRS	High-resolution infrared radiation sounder
HM	Hydrometeorological
HRV	Haute resolution visible
HSSW	High-salinity shelf water
HVAC	Heating, ventilating, and cooling
IAEA	International Atomic Energy Agency
IAGP	International Antarctic Glaciological Program
IAHS	International Association of Hydrological Sciences
IAMAP	International Association of Meteorology and Atmospheric Physics
IASH	International Association of Scientific Hydrology
IAT	Ice albedo-temperature (feedback)
ICD	International Classification of Diseases
ICRCCM	Intercomparison of Radiation Codes Used in Climate Models
ICSI	International Commission on Snow and Ice
ICSU	International Council of Scientific Unions
IEA	Institute for Energy Analysis, ORAU
IEA	International Energy Agency
IGY	International Geophysical Year
IIASA	International Institute for Applied Systems Analysis

ILS	International Latitude Service
IM	Iceberg melting
IOM	Institute of Medicine
IOS	Institute of Ocean Sciences
IPCM	Intercomparison of Parameterizations in Climate Models Project
IPHC	International Pacific Halibut Commission
IPM	Integrated pest management
IR	Infrared
IRGA	Infrared gas analyzer
IRIS	Infrared interferometer spectrometer
IRIS	International Recruitment Investigations in the Subarctic
ISCCP	International Satellite Cloud Climatology Project
ISLSCP	International Satellite Land Surface Climatology Project
ITCZ	Intertropical convergence zone
IWP	Ice water path (through a cloud)
JEG	Jacobsen and Ekblad glaciers
JJA	June-July-August
KBP	Thousand years before the present
KEY	Key Biscayne, Florida
KPA	Kitt Peak, Arizona
KUM	Point Kumukahi, Hawaii
L0F	Lithospheric model with no core
L1F	Lithospheric model with one density discontinuity
L2F	Lithospheric model with two density discontinuities
LAD	Leaf area duration
LAGEOS	Laser Geodynamics Satellite
LAI	Leaf area index
LANDSAT	Land Remote Sensing Satellite (Earth Resources Technological Satellite)
LAR	Leaf area ratio
LBL	Line-by-line
LFC	Large format camera
LLNL	Lawrence Livermore National Laboratory
LP	Linear programming
LWC	Liquid water content
LWP	Liquid water path (through a cloud)
m	Maritime
MAAT	Mean annual air temperature
MALR	Moist adiabatic lapse rate
MAM	March-April-May
MAPSAT	Mapping satellite
MAT	Marine air temperature
MB	Multibox model
MBC	Mould Bay, Canada
MBL	Marine Biological Laboratory
MIT	Massachusetts Institute of Technology
MIZEX	Marginal Ice Zone Experiment
MKO	Mauna Kea, Hawaii
MLA	Multispectral linear array
MLO	Mauna Loa, Hawaii
MONEX	Monsoon Experiment
M-SK	Midcase trajectory from Seidel and Keyes
MSL	Mean sea level
MSS	Multispectral scanner
NAE	U.S. National Academy of Engineering

NAR	Net assimilation rate
NARE	Norwegian Antarctic Research Expedition
NAS	U.S. National Academy of Sciences
NAS	North Atlantic Study
NASA	U.S. National Aeronautics and Space Administration
NBM	Narrow band model
NBS	National Bureau of Standards, U. S. Department of Commerce
NCAR	National Center for Atmospheric Research, NOAA
NECS	Net ecosystem carbon storage
NEP	Net ecosystem productivity
NESDIS	National Environmental Satellite Data and Information Service, NOAA
NFPA	National Forest Products Association
NIMBUS	Nimbus satellite
NIOSH	National Institute of Occupational Safety and Health, U.S. Department of Health and Human Services
NMAT	Nighttime marine air temperature
NMC	National Meteorological Center, NOAA
NMFS	National Marine Fisheries Service, NOAA
NOAA	National Oceanographic and Atmospheric Administration, U.S. Department of Commerce
NORPAX	North Pacific Experiment
NPP	Net primary production
NRC	U.S. National Research Council
NS	Native plant species
NSF	U.S. National Science Foundation
NTP	Normal temperature and pressure
NW	Niehaus and Williams
NWAFC	Northwest and Alaska Fishery Center, NMFS, NOAA
NWR	Niwot Ridge, Colorado
NY	Nordhaus and Yohe
NZL	Kiatorete Spit, New Zealand
OCSEAP	Outer Continental Shelf Environmental Assessment Program
OECD	Organisation for Economic Cooperation and Development
OGCM	Oceanic general circulation model
OMS	Orbital Mapping System
OPEC	Organization of Oil Exporting Countries
ORAU	Oak Ridge Associated Universities
ORNL	Oak Ridge National Laboratory
OSU	Oregon State University
OTA	Office of Technology Assessment, U.S. Congress
OWS	Ocean weather ship
PACLIM	Pacific-American Climate Variability Research
PAL	Predicted albedo
PBS	Pacific Biological Station
PC	Penetrative convection
PCL	Predicted clouds
pCO_2	Partial pressure of carbon dioxide
PCSP	Polar Continental Shelf Project
PD	Purely diffusive
PEBM	Planetary energy balance model
PEP	Phosphoenolpyruvate
PMEL	Pacific Marine Environmental Laboratory
PPFD	Photosynthetic photon flux density
PPTN	Precipitation
PROBES	Processes and Resources of the Eastern Bering Sea
PSA	Palmer Station, Antartica

PSFG	Permanent Service on the Fluctuations of Glaciers
RA	Autotrophic respiration
RBV	Return beam vidicon
RCM	Radiative-convective model
RG	Robb Glacier
RGR	Relative growth rate
RH	Heterotrophic respiration
RH	Relative humidity
RIGGS	Ross Ice Shelf Geophysical and Glaciological Survey
RISP	Ross Ice Shelf Project
RISS	Ross Ice Shelf Survey
RLGR	Relative leaf growth rate
rsl	Relative sea level
RSL	Relative sea level
RSR	Root-to-shoot ratio
RuBP	Ribulose bisphosphate
R/V	Research vessel
SAS	Statistical Analysis Systems
SAT	Surface air temperature
SCAMS	Scanning microwave spectrometer
SCAR	Scientific Committee on Antarctic Research
SCOPE	Scientific Committee on Problems of the Environment
SCOR	Scientific Committee on Oceanographic Research
SCR	Selective chopper radiometer
SEASAT	Sea satellite
SEBM	Surface energy balance model
SEY	Seychelles Islands
SIO	Scripps Institution of Oceanography
SK	Seidel and Keyes
SL	Sea level
SLA	Specific leaf area
SM1(A)	Spelman and Manabe modeling experiment 1
SM2(A)	Spelman and Manabe modeling experiment 2
SM3(A)	Spelman and Manabe modeling experiment 3
SMM	Solar Maximum Mission
SMMR	Scanning multifrequency microwave radiometer
SMO	American Samoa
SOA	State-of-the-art report
SOF	Statement of findings
SOI	Southern oscillation index
SPAR	Soil-plant-atmosphere research
SPO	South Pole
SPOT	Systeme Probatoire d'Observation de la Terra
SPRI	Scott Polar Research Institute
SPS	Sucrose phosphate synthase
SRP	Salt River Project
SST	Sea surface temperature
SST	Station surface temperature
STC	Weathership Charlie
STM	Weathership M
STP	Standard temperature and pressure
SUPER	Subarctic Pacific Ecosystem Research
t	Transitional
TA	Total dissolved alkalinity

TASU	Time alternating space uncentered
TC	Total dissolved inorganic carbon
TDS	Total dissolved solids
TM	Thematic mapper
TR	Transpiration rate
TTO	Transient Tracers in the Ocean
TTS	Temporary Technical Secretariat, WGI
T.U.	Tritium unit
TUD	Technical University of Denmark
UA	University of Alaska
UBC	University of British Columbia
UD	Upwelling diffusion
UKMO	United Kingdom Meteorological Office
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific, and Cultural Organization
UNWC	United Nations Water Conference
USDA	United States Department of Agriculture
USGS	United States Geological Survey
UV	Ultraviolet
UW	University of Washington
VAS	Visible infrared spin scan radiometer atmospheric sounder
VAW	Versuchsanstalt für Wasserbau, Hydrologie, und Glaziologie
VCC	Variable cloud cover
VEI	Volcanic explosivity index
VHRR	Very high resolution radiometer
VOD	Variable optical depth
VPD	Vapor pressure deficit
VRH	Variable relative humidity
WA	West Antarctica
WBM	Wide band model
WCRP	World Climate Research Program
WEC	World Energy Conference
WGI	World Glacier Inventory
WHO	World Health Organization
WM	Wall melting
WMCO	Primary intrusion of warm water
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment
WP	Cloud water path
WRC	U.S. Water Resources Council
WUE	Water use efficiency
WW	Well watered
WWR	World Weather Records
ZAPS	Zonal Air Pollution System

INDEX OF COMMON NAMES

This Glossary gives the scientific names associated with the common names of flora and fauna mentioned in the six CO_2 state of the art reports. In some cases, more than one scientific name is associated with a single common name and vice versa. Species for which no common name was found have been omitted.

Alaska pollack	*Theragra chalcogramma*
Alfalfa weevil	*Phytonomus posticus*
Alfalfa	*Medicago sativa*
American plane tree	*Platanus occidentalis*
Anchovy	*Anchoa* spp.
Ash	*Fraxinus* spp.
Aspen	*Populus grandidentata*
Atlantic cod	*Gadus morhua*
Atlantic herring	*Clupea harengus harengus*
Barley	*Hordeum vulgare*
Barnyard grass	*Echinocloa crus-galli*
Beggar's lice	*Desmodium paniculatum*
Black cutworm moth	*Argotis ypsilon*
Blueberry	*Vaccinium uliginosum; Vaccinium vitis-idaea*
Bluegrass	*Poa* spp.
Brahman cattle	*Bos indicus*
Bristlecone pine	*Pinus longaera*
California bristlecone pine	*Pinus aristata*
California halibut	*Paralichthys californicus*
Canary grass	*Phalaris* spp.
Capelin	*Mallotus villosus*
Catfish	*Ictalurus* spp.
Cattle	*Bos taurus*
Chlorella	*Chlorella vulgaris*
Chrysanthemum	*Chrysanthemum* spp.
Clover	*Trifolium* spp.
Common murre	*Uria aalge*
Corn borer	*Pyrausta nubilaris*
Corn	*Zea mays*
Cotton grass	*Eriophorum vaginatum*
Cotton	*Gossypium* spp.
Cottonwood	*Populus deltoides*
Coulter pine	*Pinus coulteri*
Creosote bush	*Larrea divaricata*
Cucumber	*Cucumis sativa*
Dalis grass	*Paspalum dilatatum*
Darnel rye grass	*Lolium tremulatum*
Dungeness crab	*Cancer magistar*
Dwarf arctic birch	*Betula nana*
Eastern poplar	*Populus deltoides*
Faba bean	*Vicea faba*
Festuca	*Festuca elatior*
Flatfish	*Pseudopleuronectes americanus*
Foxtail	*Setaria* spp.
Fur seal	*Callorhinus* spp.; *Arctocephalus* spp.
Giant ragweed	*Ambrosia trifida*
Grape	*Vitus* spp.
Herring	*Clupea harengus*
Hickory	*Carya* spp.
Hookworm	*Ancylostoma* spp.; *Necator* spp.
Hydrilla	*Hydrocharitaceae* spp.
Itch grass	*Roltboellia exaltata*
Jack pine	*Pinus banksiana*
Jimson weed	*Datura stramonium*
Kale	*Brasica oleracea*
Kittiwake	*Rissa* spp.
Knobcone pine	*Pinus attenuata*
Lamb's-quarter	*Chenopodium album*
Lettuce	*Latuca sativa*
Limber pine	*Pinus flexilis*
Loblolly pine	*Pinus taeda*
Lucern	*Medicago sativa*
Maize	*Zea mays*
Marsh tea	*Ledum palustre*
Millet	*Setaria* spp.
Oak	*Quercus* spp.
Oats	*Avena* spp.
Okra	*Hibiscus esculentus*
Oleander	*Nerium oleander*
Oysters	*Ostrea* spp.
Pacific cod	*Gadus macrocephalus*
Pacific hake	*Merluccius productus*
Pacific herring	*Clupea harengus pallasi*
Peanut	*Arachis hypogea*
Peas	*Pisum* spp.
Pennsylvania knotweed	*Polygonum pensylvanicum*
Pensacola Bahia grass	*Paspalum notatum*
Perrenial rye grass	*Lolium perenne*
Peruvian anchovy	*Engraulis ringens*
Phlox	*Phlox drummondi*
Pigweed	*Amaranthus retroflexus*
Pineapple	*Ananas cosmosus*
Pink shrimp	*Pandalus borealis*
Pinto bean	*Phaseolus* spp.
Plaice	*Pleuronectes platessa*

Polar bear	*Thalarctos maritimus*
Ponderosa pine	*Pinus ponderosa*
Poplar	*Populus* spp.
Rabbit bush	*Chrysothamnus visidiflorus*
Radish	*Raphanus* spp.
Red oak	*Quercus rubra*
Rice	*Oryza sativa*
Rose	*Rosa* spp.
Salmon	*Oncorhynchus* spp.
Saltbush	*Atriplex hymenlytra*
Saxifrage	*Saxifraga flagelaris*
Sea lion	*Zalophus* spp.; *Otaria* spp.
Shearwater	*Puffinis* spp.
Sheep	*Ovis aries*
Showy crotalaria	*Crotalaria spectabilis*
Sicklepod	*Cassia obtusifolia*
Silver maple	*Acer saccharinus*
Sockeye salmon	*Oncorhynchus nerka*
Sorghum	*Sorghum halapense; Sorghum bicolor; Sorghum sudanese*
Soybean	*Glycine max*
Sperm whale	*Physter catodon*
Spiny dogfish	*Squalus acanthias*
Spirulina	*Spirulina platensis*
Stiff sedge	*Carex bigelowii*
Striped bass	*Roccus saxatilis; Morone saxatilis*
Sugar beet	*Beta vulgaris*
Sugarcane	*Sacchanum officionarum*
Sunflower	*Helianthus annuus*
Sweet gum	*Liquidambar styraciflua*
Sweet potato whitefly	*Bemisia tabaci*
Sweet potato	*Ipomea batatas*
Swine	*Sus scrofa*
Termite	*Termes* spp.
Tobacco	*Tobascum nicotinana*
Tomato	*Lycopericum esculentum*
Trefoil	*Lotus* spp.
Tulip poplar	*Liriodedron tulipfera*
Tuna	*Thunnus saliens*
Upland cotton	*Gossypium hirsutum*
Velvet leaf	*Abutilon theophrasti*
Walrus	*Odobenus rosmarus*
Water hyacinth	*Eichhornia* spp.
Wheat	*Triticum aestivum*
White clover	*Trifolium repens*
White potato	*Solanum tuberosum*
Winter fat	*Eurotia lanata; Ceratoides lanata*
Yellowfin sole	*Limanda aspera*

INDEX OF SCIENTIFIC NAMES

This Glossary gives the common names associated with the scientific names of flora and fauna mentioned in the six CO_2 reports. In some cases, more than one common name is associated with a single scientific name and vice versa.

Abutilon theophrasti	Velvet leaf
Acer saccharinus	Silver maple
Amaranthus retroflexus	Pigweed
Ambrosia artemisiifolia	No common name
Ambrosia trifida	Giant ragweed
Ananas cosmosus	Pineapple
Anchoa spp.	Anchovy
Ancylostoma spp.	Hookworm
Arachis hypogea	Peanut
Arctocephalus spp.	Fur seal
Argotis ypsilon	Black cutworm moth
Atriplex hymenlytra	Saltbush
Avena spp.	Oats
Bemisia tabaci	Sweet potato whitefly
Beta vulgaris	Sugar beet
Betula nana	Dwarf arctic birch
Bos indicus	Brahman cattle
Bos taurus	Cattle
Brasica oleracea	Kale
Callorhinus spp.	Fur seal
Camissonia brevipes	No common name
Cancer magistar	Dungeness crab
Carex bigelowii	Stiff sedge
Carya spp.	Hickory
Cassia obtusifolia	Sicklepod
Ceratoides lanata	Winter fat
Chenopodium album	Lamb's-quarter
Chlorella vulgaris	Chlorella
Chrysanthemum spp.	Chrysanthemum
Chrysothamnus visidiflorus	Rabbit bush
Clupea harengus harengus	Atlantic herring
Clupea harengus pallasi	Pacific herring
Clupea harengus	Herring
Crotalaria spectabilis	Showy crotalaria
Cucumis sativa	Cucumber
Datura stramonium	Jimson weed
Desmodium paniculatum	Beggar's lice
Echinocloa crus-galli	Barnyard grass
Eichhornia spp.	Water hyacinth
Engraulis ringens	Peruvian anchovy
Eriophorum vaginatum	Cotton grass
Eurotia lanata	Winter fat
Festuca elatior	Festuca
Fraxinus spp.	Ash
Gadus macrocephalus	Pacific cod
Gadus morhua	Atlantic cod
Glycine max	Soybean
Gossypium hirsutum	Upland cotton
Gossypium spp.	Cotton
Helianthus annuus	Sunflower
Hibiscus esculentus	Okra
Hordeum vulgare	Barley
Hydrocharitaceae spp.	Hydrilla
Ictalurus spp.	Catfish
Ipomea batatas	Sweet potato
Larrea divaricata	Creosote bush
Latuca sativa	Lettuce
Ledum palustre	Marsh tea
Limanda aspera	Yellowfin sole
Liquidambar styraciflua	Sweet gum
Liriodedron tulipfera	Tulip poplar
Lolium perenne	Perrenial rye grass
Lolium tremulatum	Darnel rye grass
Lotus spp.	Trefoil
Lycopericum esculentum	Tomato
Mallotus villosus	Capelin
Medicago sativa	Alfalfa; lucern
Merluccius productus	Pacific hake
Morone saxatilis	Striped bass
Necator spp.	Hookworm
Nerium oleander	Oleander
Odobenus rosmarus	Walrus
Oncorhynchus nerka	Sockeye salmon
Oncorhynchus spp.	Salmon
Oryza sativa	Rice
Ostrea spp.	Oysters
Otaria spp.	Sea lion
Ovis aries	Sheep

Pandalus borealis	Pink shrimp	*Rissa* spp.	Kittiwake
Paralichthys californicus	California halibut	*Roccus saxatilis*	Striped bass
Paspalum dilatatum	Dalis grass	*Roltboellia exaltata*	Itch grass
Paspalum notatum	Pensacola Bahia grass	*Rosa* spp.	Rose
Phalaris spp.	Canary grass	*Sacchanum officionarum*	Sugarcane
Phaseolus spp.	Pinto bean	*Saxifraga flagelaris*	Saxifrage
Phlox drummondi	Phlox	*Setaria* spp.	Millet, foxtail
Physter catodon	Sperm whale	*Solanum tuberosum*	White potato
Phytonomus posticus	Alfalfa weevil	*Sorghum bicolor*	Sorghum
Pinus aristata	California bristlecone pine	*Sorghum halapense*	Sorghum
Pinus attenuata	Knobcone pine	*Sorghum sudanese*	Sorghum
Pinus banksiana	Jack pine	*Spirulina platensis*	Spirulina
Pinus coulteri	Coulter pine	*Squalus acanthias*	Spiny dogfish
Pinus flexilis	Limber pine	*Stylosanthus humilis*	No common name
Pinus longaera	Bristlecone pine	*Sus scrofa*	Swine
Pinus ponderosa	Ponderosa pine	*Termes* spp.	Termite
Pinus taeda	Loblolly pine	*Thalarctos maritimus*	Polar bear
Pisum spp.	Peas	*Theragra chalcogramma*	Alaska pollack
Platanus occidentalis	American plane tree	*Thunnus saliens*	Tuna
Pleuronectes platessa	Plaice	*Tidestromia oblongfolia*	No common name
Poa spp.	Bluegrass	*Tobascum nicotinana*	Tobacco
Polygonum pensylvanicum	Pennsylvania knotweed	*Trifolium repens*	White clover
Populus deltoides	Cottonwood	*Trifolium* spp.	Clover
Populus deltoides	Eastern poplar	*Triticum aestivum*	Wheat
Populus grandidentata	Aspen	*Uria aalge*	Common murre
Populus spp.	Poplar	*Vaccinium uliginosum*	Blueberry
Pseudopleuronectes americanus	Flatfish	*Vaccinium vitis-idaea*	Blueberry
Puffinis spp.	Shearwater	*Vicea faba*	Faba bean
Pyrausta nubilaris	Corn borer	*Vitus* spp.	Grape
Quercus rubra	Red oak	*Zalophus* spp.	Sea lion
Quercus spp.	Oak	*Zea mays*	Corn, maize
Raphanus spp.	Radish		

CITATION INDEX

Authors cited by name in the texts of the four State of the Art reports and the two supporting documents are listed in this index. Where a coauthor's name is subsumed under an et al. in the text, no entry for that coauthor appears in this index. The page numbers cited are grouped by report. The bold-face acronyms refer to the six reports: **GCC:** *Atmospheric Carbon Dioxide and the Global Carbon Cycle;* **DIR:** *Direct Effects of Increasing Carbon Dioxide on Vegetation;* **DET:** *Detecting the Climatic Effects of Increasing Carbon Dioxide;* **PRO:** *Projecting the Climatic Effects of Increasing Carbon Dioxide;* **INF:** *Characterization of Information Requirements for Studies of CO_2 Effects: Water Resources, Agriculture, Fisheries, Forests, and Human Health;* and **GLA:** *Glaciers, Ice Sheets, and Sea Level: Effect of a CO_2-Induced Climatic Change.*

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